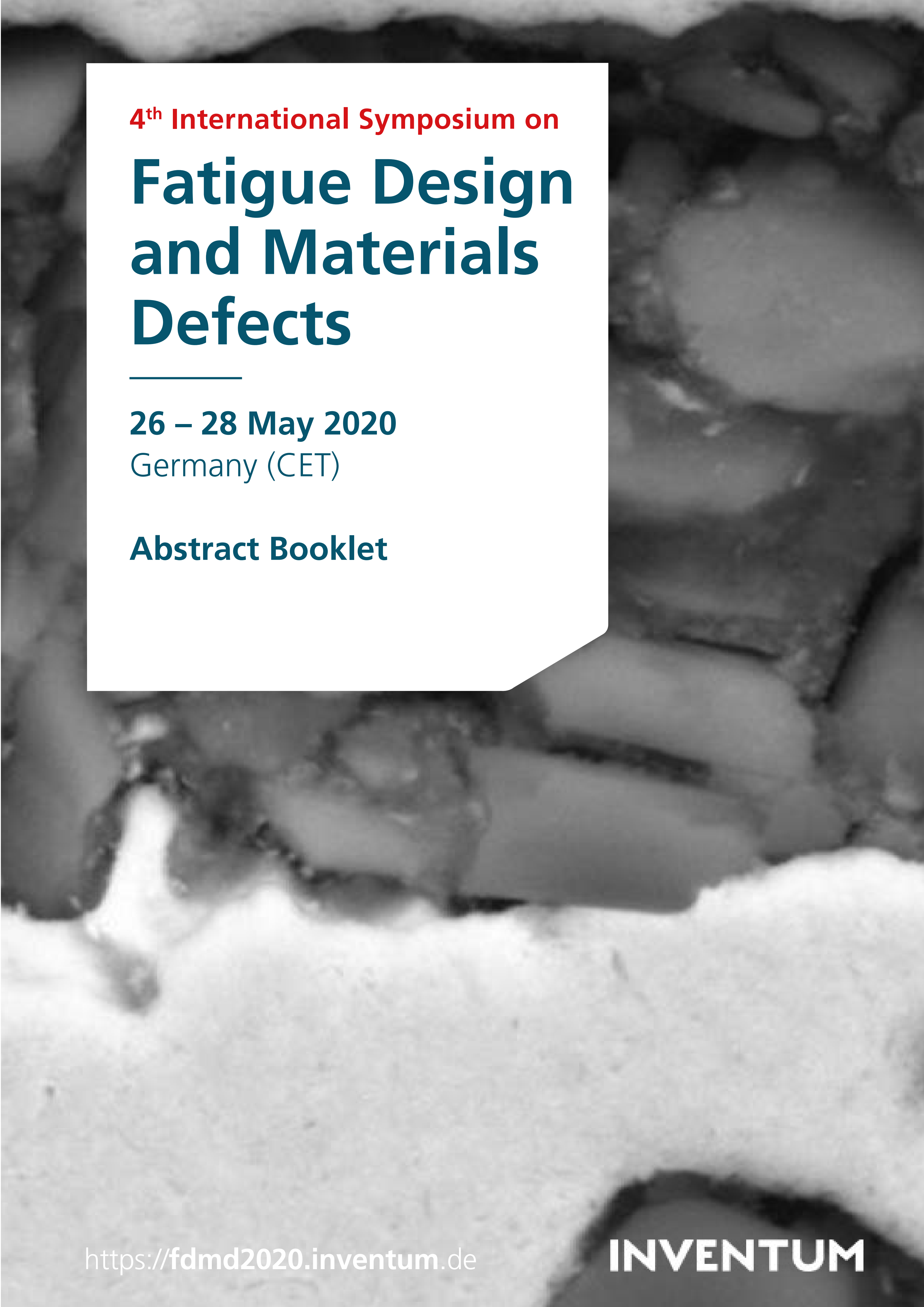

4th International Symposium on

# Fatigue Design and Materials Defects

26 – 28 May 2020
Germany (CET)

## Abstract Booklet

https://fdmd2020.inventum.de

INVENTUM

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# The Scope

Following the successful symposia in Trondheim in 2011, in Paris in 2014 and in Lecco in 2017 we wish to announce the

**4th International Symposium on Fatigue Design and Material Defects**
from May 26–28 2020 in Germany.

Material defects such as non-metallic inclusions, pores, micro-shrinkages etc. play a crucial role in fatigue crack initiation and propagation which in turn has significant consequences for structural integrity in terms of lifetime, fatigue strength and other characteristics of cyclically loaded components.

The main objectives of the symposium are to improve the understanding of the mechanisms and the impact of defects on structural integrity, and to work out measures to improve the fatigue properties of materials and components.

To that purpose presentations are welcome which address the according topics.

Be welcome at FDMD 2020!

Sincerely yours,


**Prof. Dr.-Ing. Uwe Zerbst**
Bundesanstalt für Materialforschung und -prüfung (Berlin, Germany)



**Dr. Mauro Madia**
Bundesanstalt für Materialforschung und -prüfung (Berlin, Germany)

# Programme Overview 26 & 27 May 2020

| Tuesday, 26 May 2020 | | |
|---|---|---|
| 09:00 | **Opening Address** | |
| 09:20 | **Defects and fatigue failure – An Introduction**<br>U. Zerbst (Sp) | |
| 10:00 | **Plenary:** Y. Murakami | |
| 10:40 | **Break** | |
| 11:10 | **Basic aspects** | **Aluminium alloys** |
| 12:30 | **Break** | |
| 13:30 | **Plenary:** N. Shamsaei | |
| 14:10 | **Additive manufacturing** | **Cast iron and cast steel** |
| 15:30 | **Break** | |
| 16:00 | **Plenary:** S. Münstermann | |
| 16:40 | **Additive manufacturing** | **Cast iron and cast steel** |
| 18:00 | **Welcome + Poster** | |

| Wednesday, 27 May 2020 | | |
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| 09:00 | **Plenary:** Y. Nadot | |
| 09:40 | **Basic aspects** | **Non-destructive testing and scatter** |
| 10:40 | **Break** | |
| 11:10 | **Basic aspects** | **Non-destructive testing and scatter** |
| 12:30 | **Break** | |



# Programme Overview 27 & 28 May 2020

| | | |
|---|---|---|
| 13:30 | **Plenary:** N. Hrabe | |
| 14:10 | **Additive manufacturing** | **Special applications** |
| 15:30 | **Break** | |
| 16:00 | **Plenary:** M. Chapetti | |
| 16:40 | **Additive manufacturing** | **Fracture mechanics** |
| 18:00 | **Network Evening** | |

| Thursday, 28 May 2020 | | |
|---|---|---|
| 09:00 | **Plenary:** F. Morel | |
| 09:40 | **Steel** | **Special applications** |
| 10:40 | **Break** | |
| 11:10 | **Steel** | **Special applications** |
| 12:30 | **Break** | |
| 13:30 | **Plenary:** S. Beretta | |
| 14:10 | **Steel** | **Basic aspects** |
| 14:30 | **Steel** | **Additive manufacturing** |
| 14:50 | **Steel** | **Aluminium alloys** |
| 15:30 | **Break** | |
| 16:00 | **Plenary:** Z. Benk | |
| 16:40 | **Special applications** | **Fracture mechanics** |
| 17:20 | **Closing Remarks** | |

Session **Plenary Lectures**

10:00 **Essential Structure of S-N curve: Prediction of Fatigue Life and Fatigue Limit of Defective Materials and Nature of Scatter**

Y. Murakami (Sp)[1]; K. Wada[2]; T. Takagi[3]; H. Matsunaga[1]
[1]Kyushu University, Fukuoka (Japan); [2]Fukuoka University (Japan); [3]Takagi Corporation, Kitakyushu City (Japan)

In order to elucidate the essential structure of S-N curve, this paper discusses a prediction method for fatigue life and fatigue limit of materials containing various defects and the nature of scatter of fatigue strength influenced by presence of defects.   All commercial materials contain some defects. Although graphite nodules are not inteded as a material defect from the viewpoint of metallurgy, they behave like a material defect from the viewpoint of mechanics of fatigue. Nonmetallic inclusions in bearing steels, spring steels, tool steels, etc., are a typical defect both from metallurgy and mechanics of fatigue. Defects and surface roughness in additively manufactured (AM) materials have serious influences on fatigue strength and quality control for realizing the application of AM to power components. This paper shows an extended application of the √area parameter model to not only fatigue limit but also to fatigue life in S-N data of various steels and AM materials in terms of scatter and quality control. The application of the proposed method to fatigue damage concept under variable amplitude loadings will be suggested.

13:30 **Fatigue of Additive Manufactured Materials: Design Allowables and Defect Criticality**

N. Shamsaei (Sp)[1]
[1]Auburn University (United States)

As the great potentials of additive manufacturing (AM) has urged the industry to adopt this advanced technology, there are still major challenges to be resolved. Some of these challenges include qualification, certification and standardization, as well as validated design tools. For additively manufactured parts to be trusted in load-bearing, safety-critical applications, their structural integrity must be well understood, especially under cyclic loading. Bridging this gap is a complex undertaking, as there are many challenges specific to characterizing the behavior of additively manufactured parts. Any changes in feedstock characteristics, as well as design, process, post-process parameters can greatly impact the microstructure and mechanical properties. For example, the mechanical properties of AM laboratory specimens may not be representative of those associated with service parts; this is primarily due to differences in geometry/size, which can affect the thermal histories experienced during fabrication. The variation in thermal history affects the defects inherent to additively manufactured parts such as surface roughness, porosity, and lack of fusion between subsequent layers which can negatively impact the fatigue resistance. This presentation will provide an overview of the challenges facing the community with regards to generating design allowables for additively manufactured materials and suggest that understanding the defect critically along with having access to effective nondestructive testing methods or validated process simulations might be a more reasonable solution.





16:00 **Modelling the effect of impurities on incubation and short crack growth**

S. Münstermann (Sp)[1]; J. Lian[2]; C. Gu[3]; Y. Bao[3]
[1]RWTH Aachen University (Germany); [2]Aalto University (Finland); [3]University of Science and Technology Beijing (China)

The design of new metallic materials with increased fatigue resistance is based on a quantitative understanding of microstructural influences on cyclic properties. The microstructure-sensitive fatigue modelling concept is, therefore, a key contribution to the development of new material design approaches beyond reducing the amount and maximum size of impurities.
In the contribution, the concept of microstructure-sensitive fatigue modelling will be introduced and discussed. Special emphasis is laid on the generation of statistically representative volume elements and the crystal plasticity models. Afterwards, the strategy to derive macroscopic cyclic properties from fatigue simulations is presented. Finally, a case study reveals that the residual stresses around inclusions which stem from the thermomechanical processes of material production play a vital role for the fatigue performance of the material. A strategy of residual stress consideration is therefore developed as well.

09:00 **Fatigue from defect: influence of size, type, morphology, position and loading**

Y. Nadot (Sp)[1]
[1]Ecole Navale Supérieure de Mécanique et dAérotechnique, Chasseneuil-du-Poitou (France)

Experimental results are sumarised on different metallic materials in order to point out the influence of the following parameters on the fatigue limit: size, type, morphology, position and loading (see Figure 1).

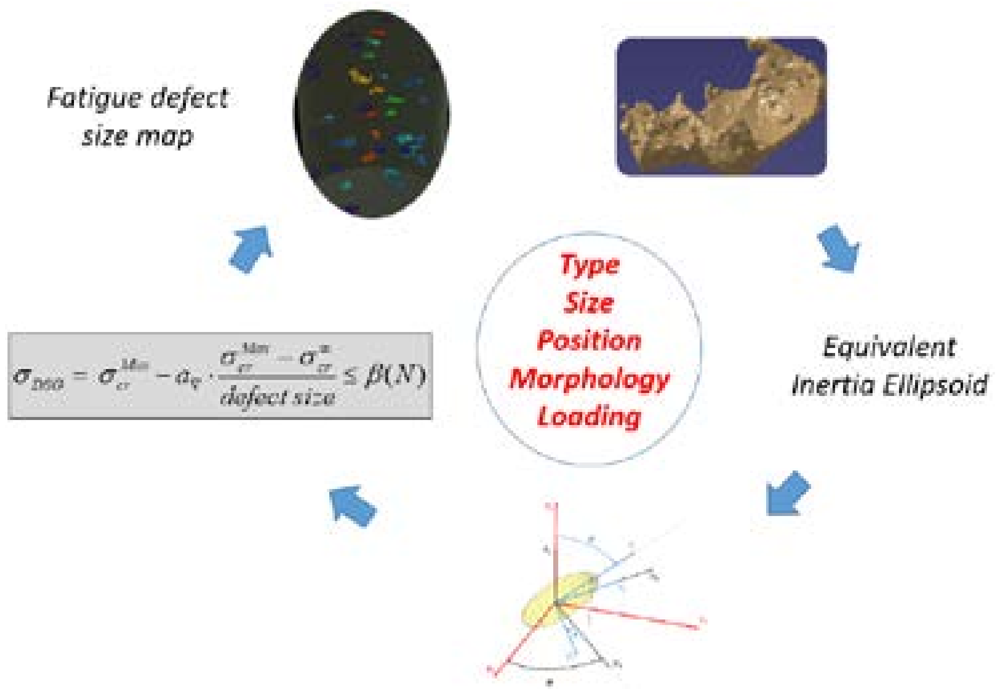


Figure 1: Modelling the influence of defect size, type, position, morphology and loading on the fatigue limit using DSG (Defect Stress Gradient) criterion

A modelling strategy is proposed to evaluate the influence of defect on the fatigue limit by
(i) computing the Equivalent Inertia Ellipse of each defect
(ii) modelling the influence of the defect on the fatigue limit through the DSG (Defect Stress Gradient) approach
(iii) 3D mapping the criticality of each individual defect.

The Methodology is validated through fatigue tests conducted on Cast materials as well as AM materials.

13:30 **High-Cycle Fatigue and Fatigue Crack Growth Rate Behavior of Additively Manufactured Titanium Alloy and the Role of Internal Porosity and Crystallographic Texture**

N. Hrabe (Sp)[1]; J. Benzing[1]; R. Rentz[1]; T. Gnaupel-Herold[1]; T. Quinn[1]; F. DelRio[1]
[1]National Institute of Standards and Technology (NIST), Boulder (United States)

This talk discusses two related investigations on elelctron beam melted (EBM) titanium alloy (Ti-6Al-4V). In the first, the effects of internal pores and residual stress on ASTM E466 constant force high-cycle fatigue (R=0.1) properties of EBM Ti-6Al-4V material in as-built, stress-relieved, and hot isostatic pressed (HIPed) conditions were evaluated. Conventional techniques were used to measure the chemical composition and quantify microstructures, and neutron scattering was utilized to measure residual stresses. Post-processing did not alter chemical composition. Compared to the as-built condition, microstructure was unchanged for stress-relieved material and coarser for HIPed material. No significant residual stresses were measured for any of the three conditions. This indicates build platform and layer preheating lead to sufficient process temperatures to achieve full stress relief in-situ. The fatigue strengths at 10^7 cycles measured for the as-built and stress-relieved conditions were statistically similar and were measured to be 200 MPa to 250 MPa. A significantly higher fatigue strength at 10^7 cycles of 550 MPa to 600 MPa was measured for the HIPed condition. The increase in fatigue endurance limit was attributed to a reduction in internal porosity. In the second piece of work, the effects of internal pores and crystallographic texture on ASTM E647 fatigue crack growth rate (R = 0.1) of EBM Ti-6Al-4V were investigated by studying material in the as-built and HIPed conditions as well as in two orthogonal crack growth directions with respect to the build direction. Both internal porosity and crystallographic texture were found to affect the onset of unstable crack growth, but neither were found to affect Paris Law behavior. Implications on threshold behavior will also be discussed.

16:00 **Fracture mechanics models for fatigue design and small defect assessment**

M. Chapetti (Sp)[1]
[1]Universidad Nacional de Mar del Plata UNMdP (Argentina)

The use of fracture mechanics based methodologies to assess the influence of defects on the high cycle fatigue resistance of mechanical components has become increasingly important for industrial applications and design. This presentation introduces the most commonly used fracture mechanics methods, emphasizing the assumptions on which they are based and analyzing their potential in predicting the influence of the main geometrical, mechanical and microstructural variables involved in the definition of the fatigue behaviour of the components. Applications examples on different configurations with small defects are presented. Special attention is paid to the example of welded joints, a complex configuration with defects, stress concentrations, residual stresses, microstructure distributions, etc. Finally, the potential of the fracture mechanics methodologies is analyzed when proposing simplifications suitable for use in the development of design documents for engineering applications.





09:00 **Size and multiaxial effects in High Cycle Fatigue – Role of microstructure and defect population**

F. Morel (Sp)[1]
[1]Ecole Nationale Supérieur des Arts et Métiers - ENSAM, Cluny (France)

The design against fatigue of metallic components is often a tough task since the highly stressed volume and the loading mode are likely to change with the applied boundary conditions and the component size and geometry.

The material variability is another important issue to deal with. For instance, some widespread manufacturing processes, like casting and additive manufacturing, are known to produce a larger distribution in microstructural features compared to wrought products for instance. This not only affects the fatigue strength but also its distribution. Therefore, a quantitative description of the fatigue performance taking into account explicitely the key microstructural parameters is becoming a major concern with regard to component integrity and reliability.

The present review aims at describing the main results of a few comprehensive studies regarding the High Cycle Fatigue of metallic materials showing a complex microstructure, with a special focus on the dependence of some well-known effects, i.e. the size and multiaxial effects, upon several microstructural features including the porosity content. Cast aluminium-silicon alloys and additively manufactured alloys are more particularly used to illustrate the fundamental role played by the defect features (size, type, shape, distribution, distance to the free surface …) on the fatigue response. In the absence of large pores, it is observed that other microstructural features (particles, local crystallographic texture …) control the crack initiation mechanisms and hence determined the fatigue performance.

Vast fatigue experimental campaigns carried out on alloys with different porosity contents and on specimens of different sizes clearly show that the scale effect and the experimental scatter are strongly defect population dependent. In this context, Computed Tomography technique is used to characterize the defect population and to get a better knowledge of the defect criticality.

It is also emphasized that a numerical probabilistic approach using random sampling can be built to adequately reflect several experimental observations including the size effect and the fatigue strength scatter. The parent defect population features, i.e. pore density and defect size distribution, are found to greatly affect the magnitude in scale effect as experimentally observed.

13:30 **More than 20 years of extreme value statistics for defects: fundamentals, developments and recent applications**

S. Beretta (Sp)[1]
[1]Politecnico di Milano (Italy)

16:00 **Material defect related fatigue design of automotive components: challenges and solutions**

Z. Benk (Sp)[1]
[1]Robert Bosch GmbH, Stuttgart (Germany)

Bosch as a partner for car manufacturer and supplier in the automotive industry develops and produces metallic components, e.g., in the area of electrified cars as well as for cars with internal combustion engines. Thus, one main objective is to provide reliable components with robustness against, i.e., fatigue to fulfill customer requirements. Moreover, it has to be considered that there will be components delivered with high lot sizes, high quality while keeping costs low. Therefore, a very accurate fatigue design and development of materials are necessary. In order to ensure safe use of the components, the existence of natural material defects such as non-metallic inclusions or defects caused by corrosion attack have to be considered. The present presentation gives an overview of some challenges related to fatigue design of automotive components and possible evaluation methods under consideration of defects by using fracture mechanics approaches.





Session **Additive manufacturing**

14:10 **Influence of defects on the fatigue strength of additively manufactured specimens made of aluminum**

P. Yadegari (Sp)[1]; H.T. Beier[1]; M. Vormwald[1]
[1]Technische Universität Darmstadt (Germany)

In the case of additively manufactured components made of aluminium, failure under cyclic loading is often caused by manufacturing defects such as pores or non-metallic inclusions. The size, location and frequency of these defects are directly influenced by the process parameters of the additive manufacturing process. An optimization of these parameters with regard to reduced porosity is therefore of great interest.
Within this work, the fatigue strength of four different test series on AlSi10Mg specimens produced by selective laser melting is determined. The parameter sets differ with regard to the process parameters volume rate and volume energy density. By fractographic examinations, the failure relevant defects are localized and the position and size of these defects are investigated in terms of their effect on the occurrence of failure. The high dispersion of the test results is reduced by adapted concepts of Murakami and Kobayashi through determination of a strain-based intensity factor $K_\varepsilon$ with exact consideration of the respective pore situation. Despite serious differences in porosity of the four test series, a single significant Wöhler curve with reduced scatter can be determined for all experiments on the basis of this fracture mechanics-based parameter.
Statistical evaluations of the defect size and position on the fracture surface also provide information on which values of the volume rate and volume energy density are to be preferred for selective laser melting of AlSi10Mg with regard to high fatigue strength and low porosity.

14:30 **Fatigue behavior of maraging steel fabricated by conventional route and Laser Powder Bed Fusion**

S. Schettler (Sp)[1]; R. Kühne[2]; P. Lepper[2]; M. Zimmermann[1]
[1]Technische Universität Dresden (Germany); [2]Fraunhofer Institute for Material and Beam Technology IWS Dresden (Germany)

High strength steels, particularly maraging steels, are essential for injection mold and casting mold tools. Nowadays, these tools are produced by means of Laser Powder Bed Fusion (LPBF) process, which significantly expands design freedom and opens up new possibilities for shape optimization in comparison to conventional tools. With increasing knowledge of this innovative process technology, the interest on LPBF boosts in many industrial sectors. However, for safety-relevant technical applications a comprehensive understanding of the correlation between the fabrication process route, the resulting microstructure and the associated effects on mechanical properties are crucial. As a result, materials produced by additive manufacturing have become a key issue in the field of material characterization and testing. At first glance, the strength properties of additively manufactured (AM) materials are often considered as very promising, due to yield and tensile strength reaching the level of wrought material. Meanwhile, currently available fatigue results for AM materials provide quite a different picture. This, however, is not surprising, because the fatigue behavior is significantly influenced by minor changes in the microstructure. Effects such as the cyclical thermal entry and defect features, for instance, lack of fusion or micro-pores have a huge influence on the cyclic behavior of the material.
For the future application of AM materials, it is necessary to gain a detailed understanding of the likely discrepancies in failure mechanisms of cyclically loaded additively and wrought manufactured material. Establishing reliable process-structure-property correlations allows a shape-optimized component design and a safe operation during the component lifetime. This study will focus on results regarding the fatigue behavior and failure mechanisms of 18Ni300 maraging steel (1.2709) fabricated by the conventional route and LPBF technologies. Based on tests from low to very high cycle fatigue range realized with ultrasonic fatigue testing equipment, the influence of the fabrication route on the mechanical properties will be shown. From the results, it is concluded, that the durability of AM-maraging steel is sensitive to small defects.

14:50 **Advanced characterization techniques for fatigue life estimation of additively manufactured metal samples and complex geometries**

F. Stern (Sp)[1]; D. Kotzem[1]; F. Walther[1]
[1]TU Dortmund University (Germany)

Additive manufacturing (AM) is an indispensable element for manufacturing of future light-weight and resource-saving components which are increasingly important for aerospace and energy applications. However, due to the high variability in AM techniques as well as corresponding process parameters many different material conditions can be created. Additionally, size and amount of specimens often limit a comprehensive scope of testing. Therefore, new characterization techniques have to be established in order to time-efficiently determine the cyclic material behavior of AM metals based on a small amount of samples.
Within this work, different specimens manufactured by laser (L-PBF) and electron beam powder bed fusion (E-PBF) were investigated. In particular, L-PBF manufactured steel 316L and E-PBF manufactured Inconel 718 were present as conventional specimens or as complex structures, respectively. As only a limited amount of samples was available, so-called multiple amplitude tests (MAT) on a servohydraulic testing system were conducted to estimate the fatigue behavior and strength of the investigated Fe and Ni alloys. Supplementary, mechanical, thermometric, electric and acoustic measurement techniques were introduced to detect specific material reactions. Based on this, it can be demonstrated that damage development leads to characteristic material reactions which were reliably detected by the aforementioned measurement techniques. In particular, thermometric and electric measurement techniques are highly recommended, since change in temperature or electrical resistance are sensitive for damage evolution, showing that continuous monitoring is applicable for AM samples and structures. Further on, first material reaction in MAT can be used to estimate the fatigue behavior time- and cost-efficiently, so that the influence of different process parameters or material conditions can be characterized in a reliable manner.

15:10 **Effect of post treatments on the fatigue properties of EBM Ti-6Al-4V**

J. Buffiere (Sp)[1]; T. Persenot[2]; M. Guilhem[3]; A. Burr[3]; R. Dendievel[3]
[1]Université de Lyon, Villeurbanne (France); [2]INSA-Lyon, Villeurbanne (France); [3]INP Grenoble (France)

Additive manufacturing (AM), can be used to produce complex 3D geometries which offer a large potential for weight reduction. The evaluation of the fatigue properties of such geometries is for the moment a bottleneck for their widespread use. In the literature researchers have extensively evaluated fatigue properties of AM materials on machined samples. During this machining step any defect initially present on the surface is removed (while internal ones might appear on the newly created surface). If this is a reasonable approach for designing components where a minimal machining can be applied to critical areas, in the case of complex geometries (e.g. lattices), the machining step is clearly more difficult if not completely impossible.
The objective of this work is to study the fatigue properties of Ti-6Al-4V thin samples produced by Electron Beam Melting (EBM). These samples are used to mimic the beams which are the „elementary bricks" of lattice structures. Fatigue mechanisms of those elementary struts have been first identified from cyclic tension-tension tests (constant stress amplitude R=0.1) performed on 2 mm diameter hour glass specimens. The geometrical features inherited from the EBM process: porosity, surface irregularities, roughness have been systematically characterized by laboratory X-ray tomography before the fatigue tests. SEM and tomographic observations of the fracture surfaces reveal that crack initiation always occurs at the surface from thin and relatively deep (up to 200 µm) notch-like defects. The fatigue resistance of as-built samples is therefore relatively low [1]. Chemical etching, hot isostatic pressing as well as ultrasonic blasting [2] have been performed on the as built samples. The effect of those post treatments on fatigue properties are investigated and related to the "healing" of the aforementioned defects.
References

[1] T.Persenot et al. Int. Jal Fat. 118 (2019) 65–76
[2] T.Persenot et al. Add. Manuf. 28 (2019) 821-830





16:40 **Correlating defects to fatigue properties of selective laser melted Al-Si-Mg alloys for additive manufacturing**

S. Ahmed (Sp)[1]; P. Withers[1]; M. Roy[1]; Y. Zhang[2]
[1]The University of Manchester (United Kingdom); [2]TWI Ltd., Cambridge (United Kingdom)

Additive manufacturing (AM) is a disruptive technology for many high-value applications in the biomedical, automotive, and aerospace industries. It has the potential to produce topographically optimized parts consisting of complex geometries previously not possible by traditional subtractive manufacturing methods. However, fatigue properties of powder based selective laser melting components are significantly reduced owing to inherent porosity within them as a consequence of the layer-wise solidification of these components. In order for AM components to be substituted for existing applications, the challenge is to demonstrate enhanced, if not comparable fatigue properties to standard manufacturing approaches. For Al-Si-Mg alloys which are for higher performance, lighter weight, and reduced ecological impact, fatigue is a critical factor. Intrinsic pores amongst other defects act as stress concentrators for fatigue crack initiation during high cycle fatigue. These defects can be caused by entrained gas or hydrogen evolution, as well as lack of fusion. Here in order to better understand their fatigue behavior, the distribution, morphology, size, and shape of these defects have been studied using X-ray CT prior to fatigue testing in order to correlate critical pores observed on the fracture surface, to their original form and location. Further, fatigue properties of a wrought Al-Si-Mg alloy are quantified in the high cycle fatigue regime, alongside additively manufactured AlSi10Mg alloy to quantify and understand the detrimental effect of the defect population.

17:00 **Fatigue strength of corroded 316L stainless steel manufactured by laser powder bed fusion.**

P. Merot (Sp)[1]; F. Morel[2]; E. Pessard[2]; L. Gallegos Mayorga[2]; P. Buttin[1]; T. Baffie[3]
[1]CEA Tech en Pays de la Loire et Bretagne, Bouguenais (France); [2]Arts et Métiers, Angers (France); [3]CEA-LITEN, Grenoble (France)

Fatigue in a corrosive environment has been identified as highly detrimental to the mechanical strength of metallic alloys [1]. In the case of the 316L stainless steel grade, pitting corrosion is observed, leading to localised sharp defects critical to its high cycle fatigue behaviour [2]. Indeed, cracks have a tendency to initiate on such defects on prone to pit materials.
The work hereby presented focuses on 316L specimens produced by Laser Powder Bed Fusion (L-PBF) additive manufacturing and subsequently machined and polished. This preparation was carried out to ensure the characterization of the core and not the raw surface of the elements. Metal powder was horizontally layered, meaning, perpendicular to the loading axis of the specimens. As consequence of the L-PBF process, defects such as lacks of fusion are present in the material [3]. The fatigue response of three batches corresponding to three configurations of surface integrity are investigated: (i) No corrosion before fatigue testing, (ii) corroded samples under potentiodynamic anodic polarization conditions in a neutral NaCl solution before fatigue testing and (iii) samples with hemispherical machined defects. Fracture surface observations on the first batch showed in every sample initiation from a lack of fusion surface pore. Fatigue strength obtained was in good agreement with the literature. In the second batch, some cracks initiated on corrosion pits depending on the severity of the corrosion applied to each sample and its initial population of defects. Correlation between the square root of the projected area of the initiating defect [4] and the fatigue strength was observed for both pits and lacks of fusion on a Kitagawa-Takahashi diagram. Hemispherical machined defects seemed less harmful than pits and pores from a fatigue life perspective. Defect morphology didn't appear to be the only driving force for crack initiation as a pit is closer to a machined defect than a flat lack of fusion in terms of shape. The competition between lack of fusion, corrosion pit and machined defects is studied and further discussed in this paper.

[1] Q.Wu et al., 2017.
[2] M. El May et al., 2013.
[3] R. Shrestha et al., 2016.
[4] Y. Murakami and M. Endo, 1994.

17:20 **Short Fatigue Crack Propagation from Surface Pores of an Additive Manufactured Ti-6Al-4V**

E. Akgun (Sp)[1,2]; X. Zhang[2]; M. Doré[1]; Y. Zhang[1]
[1]TWI Ltd., Cambridge (United Kingdom); [2]Coventry University (United Kingdom)

Today, it is common to achieve bulk density above 99% by using powder-based metal additive manufacturing (AM) techniques. Yet, process-induced defects remain as one of the most important source of failure under cyclic loading. This work reports fatigue testing of titanium alloy Ti-6Al-4V, focusing on the behavior of surface porosity, which could be labelled as a "semi-natural" defect. It is typically formed during post-processing stage, when process-induced, embedded pores become exposed to the free surface by the necessary material removal work to achieve desired geometry or required surface quality. Surface pores have been shown in literature to be more detrimental than embedded defects, hence the important of this study.
A typical route is followed to obtained surface pores: First, cylindrical rods of Ti-6Al-4V with 14mm diameter and 120mm length manufactured by using Electron Beam Melting (EBM) process. Afterwards, flat dog-bone samples were created by subsequent machining and polishing work to remove machining marks. Surface pores on the gauge section have been counted and quantified by using optical imaging. Silicon rubber compound replicas are utilized during the load-controlled, uniaxial fatigue testing to monitor crack initiation and short crack behavior. Based on the initial analysis, following conclusions are made:

(1) Planar type, crack-like Lack of Fusion (LoF) defects are more detrimental than pores under fatigue loading. In one test, a LoF defect found outside the gauge length led to failure in spite of many pores observed within the gauge section.
(2) Non-propagating cracks initiating from pores were observed, which further corroborates the usage of Kitagawa-Takahashi approach for critical analysis of AM Ti-6Al-4V in presence of defects.
(3) Crack growth follows a tortuous path initially, suggesting microstructural influence during the short crack regime. This effect needs to be considered in predictive modelling either by mechanistic models, e.g. crystal plasticity, or empirical factors as commonly used in engineering designs.

17:40 **VHCF response of an SLM AlSi10Mg alloy: effect of specimen volume**

A. Tridello (Sp)[1]; J. Fiocchi[2]; C.A. Biffi[2]; G. Chiandussi[1]; M. Rossetto[1]; A. Tuissi[2]; D.S. Paolino[1]
[1]Politecnico di Torino (Italy); [2]CNR ICMATE – Institute of Condensed Matter Chemistry and Technologies for Energy, Lecco (Italy)

It is well known in the literature that the fatigue response of parts produced through Additive Manufacturing (AM) processes is mainly controlled by the defect population and, in particular, by the defect size. Therefore, for a proper and safe design of AM components subjected to critical fatigue loads the defect size in the component volume should be known or reliably estimated. To this aim, the X-ray microcomputed tomography (microCT) technique can be usefully used for a non-destructive assessment of the most critical defect in AM parts and, consequently, for the estimation of the fatigue response. However, this technique is rarely adopted since it is very expensive and time consuming. An alternative faster and cheaper method considers the defects originating the fatigue failure of small specimens during laboratory tests. In this second case, size-effect must be carefully taken into account. Investigation of size-effects on the fatigue response of AM parts has been rarely studied in the literature, especially if the Very-High-Cycle Fatigue (VHCF) region is considered.
The present paper aims at assessing size-effects on the VHCF response of AlSi10Mg specimens produced through the Selective Laser Melting (SLM) process. Ultrasonic fatigue tests have been carried out on Gaussian specimens with large risk-volume and hourglass specimens built in horizontal direction. Fracture surfaces have been observed by using the Scanning Electron Microscope in order to investigate the failure origin. Size-effect has been finally statistically assessed by considering the models proposed in the literature.





14:10 **Damage tolerant design of metallic AM parts**

T. Werner (Sp)[1]; U. Zerbst[1]; M. Madia[1]
[1]Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin (Germany)

Additive Manufacturing (AM) opens new possibilities in the design of metallic components, including very complex geometries (e.g. structures optimized for certain loads), optimization of materials (e.g. gradient materials) and cost-effective manufacturing of spare parts. In the recent years, it has been used for the first safety-relevant parts, but the consideration of cyclic mechanical behavior in AM is still at the very beginning. The reason for this is the complexity of mechanical material properties, i.e. inhomogeneity, anisotropy and a large number of defects frequently textured and characterized by large scattering in size. Additionally, high surface roughness and residual stresses with complex distributions are typical of AM. Due to these reasons, the transferability of experimentally determined properties from specimens to components is a challenge. This presentation provides an overview of the questions concerning the application of AM to safety-relevant components. Possible strategies for the fatigue design of such components are presented. Besides the Kitagawa-Takahashi-diagram method and the cyclic R-curve analysis as approaches for damage-tolerant design, the identification of critical locations, the problem of representative material properties and the handling of residual stresses are addressed.

14:30 **Influence of porosity on the fatigue strength for additively manufactured Inconel 718**

L. Marcin (Sp)[1]; H. Sistach[1]
[1]Safran Aircraft Engines, Moissy-Cramayel (France)

Nowadays, the development of additive manufacturing processes allows to manufacture metal parts of complex geometries integrating new functionalities and reducing the mass of components. However, the fatigue behavior of materials fabricated via additive manufacturing is currently not well understood. Particularly, this technique potentially leads to process induced defects such as pores due to the entrapment of argon gas in the powders or the lack of fusion of the metal powder. Location, size, density, pore shape are the major contributors to the variability of the fatigue strength. Despite major research efforts on parameter optimization and control in additive manufacturing, achieving a default-free part with a uniform microstructure is a remaining challenge.
For this purpose, it is necessary to improve the understanding of the relation between the process parameters, the thermal history, the solidification, the resulting microstructure and the mechanical behavior.
The purpose of this work is to evaluate the effect of internal porosity on the fatigue strength of Inconel 718 obtained by the Selective Laser Melting process [1].
In this contribution, dedicated specimens with internal pores (spherical or lenticular shape) were manufactured [2]. Then, high cycle fatigue test under tension loading was performed and analyze to understand initiation mechanisms and highlight the debit in the fatigue strength limit. Fracture mechanics approach was used to correlate the test results and to determine the fatigue strength limit with the effect of porosities [3].

[1] D. Zhang, Z. Feng, C. Wang, W. Wang, Z. Liu, et W. Niu, « Comparison of microstructures and mechanical properties of Inconel 718 alloy processed by selective laser melting and casting », Materials Science and Engineering: A, vol. 724, p. 357-367, 2018.
[2] O. Andreau, « Deterministic defect generation in selective laser melting: parametric optimization and control », Lasers in Manufacturing Conference 2017, 2017.
[3] E. Pessard, D. Bellett, F. Morel, et I. Koutiri, « A mechanistic approach to the Kitagawa–Takahashi diagram using a multiaxial probabilistic framework », Engineering Fracture Mechanics, vol. 109, p. 89-104, 2013.

14:50 **On the role of defects on high cycle fatigue properties of austenitic stainless steel 316L produced via laser powder bed fusion process**

M. Shahriarifar (Sp)[1]; M. Doré[2]; X. Zhang[1]; M.K. Khan[1]
[1]Coventry University (United Kingdom); [2]TWI Ltd., Cambridge (United Kingdom)

Powder bed based additive manufacturing techniques have been gaining an impressive and growing attention owing to their ability to fabricate near-net shape parts with complex geometries. However, the presence of process-induced defects such as gas pores and lack of fusion has detrimental impact on the mechanical behavior of the AM components. These defects can act as stress raisers reducing the strength of the material especially under fatigue loading. The aim of this work is to elucidate the influence of defects on the high cycle fatigue strength of austenitic stainless steel 316L produced by laser powder bed fusion (L-PBF) process. As-received virgin and recycled powders were used to produce two batches of specimens resulting in different levels of defects in each batch; samples built by recycled powders were found having higher defect population. Optical and electron microscopy were employed for characterization of the microstructure. Tensile and force controlled fatigue tests were carried out on these two groups of specimens. X-ray micro-computed tomography was utilized for characterization of defect size distribution in fatigue test specimens. Fractography on fatigue specimens revealed the size and location of the crack-initiation defect. Different fatigue life prediction models are used to investigate the fatigue cracking phenomenon. Preliminary results indicate that samples produced from virgin powder (Batch A) are almost fully dense with a few small spherical gas pores (less than 100 µm diameter), whereas larger pores and lack of fusion defects of irregular shape were observed in specimens fabricated from recycled powders (Batch B). Re-use of powders is currently practiced in additive manufacturing; its effect on mechanical properties is a topic of current research. Samples from both batches have similar yield and tensile strengths, which are higher than the wrought material with the strength of batch A slightly higher than that of batch B. However, the ductility of the specimens produced from recycled powders was found to be significantly lower than specimens from virgin powders.

15:10 **Near-surface structural features and directional fatigue behavior of as-built L-PBF AlSi10Mg**

R. Konecna (Sp)[1]; G. Nicoletto[2]; E. Riva[2]; L. Kunz[3]
[1]University of Zilina (Slovakia); [2]University of Parma (Italy); [3]Brno (Czech Republic)

Laser powder bed fusion (L-PBF) makes it possible to produce metallic parts directly from a computer-aided design file. The automotive and aerospace industries have demonstrated significant attention for the L-PBF production of AlSi10Mg parts due to lightweight, hardenability and low powder cost. In addition, localized melting of gas atomized powder by a concentrated laser beam and subsequent solidification and cooling generates refined structures achieving mechanical strength competitive with conventionally produced Al-alloys. If left untreated after fabrication, residual stresses are expected in untreated parts and residual stresses superpose on operating stresses introducing an often unpredictable influence on the part durability. As-built surface quality also affects negatively the fatigue strength of L-PBF AlSi10Mg. However, surface machining is not only costly but often impossible on many L-PBF parts considering their geometrical complexity.
This study investigates the fatigue behavior of L-PBF AlSi10Mg under the combined influence of the untreated state and the as-built (i.e. rough) surface. Therefore, four sets of miniature specimens each with a different orientation with respect to the build direction were produced with a SLM 290 system (SLM Solutions, Germany) working at 50 µm layer thickness and using the recommended process parameter. Each set consisted of approx. 15 specimens. As-built specimens were tested in cyclic plane bending at load ratio R=0 and frequency of 25 Hz.
The high cycle fatigue response of L-PBF AlSi10Mg was quantified and a strong directional behavior determined with one horizontal orientation of the specimens reaching twice the fatigue strength of the vertical specimen orientation. Such a difference cannot be explained only considering surface roughness.
To investigate the origin of the directional fatigue behavior, specimens for each orientation were examined using: i) metallographic techniques to determine the near surface material structure and quality in dependence of local process parameters, ii) micro hardness mapping to quantify near-surface structural gradients due to printing sequence and iii) EBSD in the SEM to characterize crystallographic texture.





16:40 **A fracture mechanics-based approach to fatigue of additively manufactured maraging steel specimens**

G. Meneghetti (Sp)[1]; D. Rigon[1]
[1]University of Padova (Italy)

Recently, the authors have investigated the fatigue strength of additively manufactured (AMed) maraging steel specimens, where the effects of building orientation and ageing heat treatment were analysed. The main outcome of this preliminary study highlighted the importance of adopting a local damage parameter due to the presence of defects within AMed materials. Since the defects can be considered as a short cracks-like, it is deemed to be more appropriate the use of Linear Elastic Fracture Mechanic (LEFM) approaches than the classical nominal approaches for the characterization of the fatigue behavior of AMed materials. Starting from this assumption, in the present contribution, new axial fatigue tests were carried out on AMed maraging steel specimens produced by two different AM systems (EOS Gmbh and SISMA SpA) as well as axial fatigue tests were carried out on wrought maraging steel specimens both in annealed and in aged condition. Stress Intensity Factor (SIF) based on the Murakami's parameter √area was selected as LEFM parameter in which its evaluation was done after failure by analysing the √area of the killer defects observed on the fracture surfaces of all the AMed specimens. Furthermore, the SIF have been also corrected by the El-Haddad-Smith-Topper parameter a0 to take into account the influence of defects on the fatigue strength of the here considered material. Due to the lack of expensive experimental data for determine the relevant material length parameter a0, a novel rapid method to approximately evaluate a0 has been proposed. In particular, it consists in matching El-Haddad-Smith-Topper model with Murakami's expression of the threshold range of mechanically short cracks. The advantage of the adopted engineering approach is that only Vickers hardness of the material is necessary. Stress intensity factor-based design curves were obtained for all the AMed test series, showing a reduction of the scatter index from 8% to 58% with respect to the nominal stress amplitude curves (an example is reported in the figure). At the end, the stress intensity factor-based design curve was also adopted to estimate the fatigue strength of sharp V-shaped notches characterized by a reduced notch opening angle.

17:00 **Study on high cycle fatigue behavior and life prediction for the selective laser melted Ti6Al4V alloy**

H. Yu (Sp)[1]; Z. Jiao[1]; X. Wu[1]; L. Wu[1]; R. Xu[1]
[1]Beijing Institute of Aeronautical Materials (China)

Selective laser melting (SLM), as one of the most popular additive manufacturing (AM) techniques, shows more and more utilization potentialities in today's aviation industry. In order to ensure safe operation of SLM parts, it is important to have their fatigue lives well-predicted and assessed. In this study, the axial high cycle fatigue tests were carried out systematically for SLM produced Ti6Al4V alloy at room temperature (RT) and 400°C. The effects of defect, direction and temperature on fatigue lives are revealed. Pores located at surface and subsurface of the fatigue specimens are certified to be the main origin of fatigue failure. Through statistic method, the median initial pore (seen as semi-elliptical small crack) size were confirmed. The artificial flaw with the same size was made at the surface of one kind of plate specimen using the focused ion beam (FIB). The small crack growth behavior initiated from the surface artificial flaw of the plate specimen was observed using SEM in-situ fatigue system. Based on the da/dN-ΔK data of small cracks and long cracks of different stress ratios, the da/dN-ΔKeff baseline was obtained according to the Newman crack closure model. From the acquired initial small crack size and the baseline data, the total fatigue lives of SLM produced Ti6Al4V alloy were predicted by FASTRAN program. The prediction curves were evaluated by fatigue experiments. The results showed that the prediction curves agree well with the experiment data of different stress ratios.

17:20 **The improved Kitagawa-Takahashi fatigue diagram of selective laser melted Ti-6Al-4V alloys via X-ray tomography**

S. Wu (Sp)[1]; Y. Hu[1]; Z. Wu[1]; P.J. Withers[2]
[1]Southwest Jiaotong University, Chengdu (China); [2]The University of Manchester, (United Kingdom)

The intrinsic microstructures and defects introduced by selective laser melting determine the mechanical and fatigue performance of final shaped parts. Here the grain type, shape and size were characterized using electron backscattered diffraction. The high-resolution synchrotron radiation and industrial microfocus X-ray computed tomography were adopted to identify the porosity and lack of fusion defects in terms of density, morphology and dimension. The larger-sized defects in comparison with α´ grains are more sensitive to the cracking behavior, typically leading to lower fatigue strength and larger life variation. It is found that the fatigue failure tends to originate from larger incomplete fusion defects near the material surface. Then the fatigue strength in presence of defects was evaluated in combination of statistics of extremes and Murakami approach. Finally, an improved Kitagawa-Takahashi diagram was well established based on the concepts of defect-tolerant design and fracture mechanics, including the safe life region and the defect-induced fatigue life in the finite life region.

17:40 **Mechanical Effects of Manufacturing Defects in Components**

B. Lauterbach (Sp)[1]; J. Fieres[1]; K.-M. Nigge[1]
[1]Volume Graphics GmbH, Heidelberg (Germany)

Defects such as porosity are inherent in e.g. 3d printing or casting processes and may critically influence the mechanical properties of the manufactured components. Local stress concentrations around pores or other defects, might reduce the load bearing capacity and the fatigue performance. Therefore, it would be desirable to include a quantification of the detrimental effect of pores in the structural performance assessment of a component.

An application of classical FEM simulation to this problem requires a geometry conformant mesh which does not only represent the external surface of the component but also the much more complex internal surfaces resulting from the pores. Due to the potentially high number and small size of the pores, the time required to generate such a mesh and the computational effort for the simulation may quickly increase beyond practical limits. Recently, immersed-boundary finite element methods have been used to overcome this meshing problem. This approach is implemented in the Structural Mechanics Simulation module of VGSTUDIO MAX by Volume Graphics. It simulates local stress distributions directly on computed tomography (CT) scans which accurately represent complex material structures and internal discontinuities.

As a validation of this simulation approach, several studies were conducted for various types of 3D printed components to compare the simulation results with experimental tensile tests. In the experimental tensile tests, the load was increased up to the point where macroscopic fracture of the components was observed. Both the tensile strengths as well as the locations where the first cracks occurred were in good agreement between simulation and experiments.

The simulation approach presented here can be used to determine the influence of defects or shape deviations on the mechanical stability. This can be done by simulating the internal stress distributions for both a CAD model of the ideal component and one or multiple CT scans of prototypes or manufactured parts. Based on a numerical comparison of the results, it is possible to determine whether or not defects or shape deviations of the actual components lead to local stress peaks which are significantly higher than those found in the ideal component.





Session **Aluminium alloys**

11:10 **Experimental investigation on the influence of small defects on fatigue life of 7075-T6511 aluminum alloy and of 1020 steel**

E. Mamiya (Sp)[1]; N. Torres[1]; V. Rodrigues[1]; F. Castro[1]
[1]University of Brasilia (Brazil)

This work addresses the influence of small surface defects on the fatigue life of two materials, 7075-T6511 aluminum alloy and 1020 steel, under fully reversed tension-compression. Artificial defects with different shapes (cylindrical, oblong and spherical cap) and dimensions produced by milling or indentation were investigated. Defect sizes ranged from 360 to 750 micrometers, and depths varied from 9 to 750 micrometers. The study focused on fatigue lives from 10^4 to 10^7 cycles. The milled defects decreased the fatigue lives by a factor of up to two hundred for the 7075 alloy and up to nine for low carbon steel. For defects produced by indentation, fatigue life reduced up to thirty times relative to those observed in smooth specimens. In all cases, the lower the stress amplitude, the higher was the fatigue life reduction. The characteristics of the small defects (square root of area, length, depth) were observed to have different influences on fatigue life. Defects with the same square root of area but distinct aspect ratios resulted in different life reductions.

11:30 **The application of medium high strength aluminium alloys in fatigue loaded automotive parts and aspects of material temper and microstructure**

O. Jensrud (Sp)[1]
[1]SINTEF Raufoss Manufacturing AS (Norway)

The advantage of using medium to high strength aluminium alloys like the AA6082 in fatigue loaded parts in automotive chassis are many, of importance are the strength to weight ratio and high resistance to corrosion.
On the other hand, the combination of formability and high degree of forming technological freedom in producing parts are as well key factors. Processes like casting, extrusion, rolling or forging can give high quality parts for automotive applications in strong competition with steel solutions. To utilise the material the combination of chemical composition and the thermomechanical processing (TMP) should be understood since there is a strong relation to final product performance and in inherent properties. The fatigue is as critical as any other property with respect to be influenced by microstructural features as grain size, particle structure and hardening temper.
In the area of forgings experimental work with the AA6082 strongly link the recrystallized grain size in the final product to fatigue lifetime, a reduction of cycles to failure can be reduced by a factor of 10. In case of coarse grains, the ductility also decreases, and the overall product performance drops significantly if the recrystallization behaviour not properly controls during TMP.
Another issue is the hardening temper where in many cases the maximum hardness is chosen as final state of the properties. When plastic capacity and cyclic work hardening is a part of the discussion as in low cycle fatigue regime, the max hardness is contradiction. From temper T6 to an overaged temper T7X a significantly change in plastic response occurs. Correct ageing procedure should be chosen in cases of optimised design in a low cycle fatigue situation, typical for many chassis' parts.
The automotive industry is searching for lightweight solutions to meet emission regulations. However, the material and thermomechanical process integration must have a focus on microstructural issues in the final product to reach this performance demand.

11:50 **Experimental and simulative analysis of the crack tip field in the near threshold regime in aluminum alloy EN AW 608²**

A. Brückner-Foit (Sp)[1]; M. Wicke[1]; M. Diehl[2]; T. Kirsten[3]; M. Zimmermann[3]; H.-J. Christ[4]
[1]University of Kassel (Germany); [2]Max-Planck-Institut für Eisenforschung GmbH, Düsseldorf (Germany); [3]Technische Universität Dresden (Germany); [4]University of Siegen (Germany)

Long cracks in the near threshold regime can show extension characteristics which are similar to those of short cracks. One interesting feature is retardation at obstacles such as precipitates, the other one is crack extension along crystallographic planes. Both phenomena have been observed both for through-wall cracks and for surface cracks. This behavior is traced back to the crack tip field in the present paper. For this purpose, the three-dimensional microstructure in the vicinity of the crack tip was resolved by combining high resolution X-ray tomography and microstructure analysis in the SEM. These investigations yield the three-dimensional geometry of the crack faces, the surrounding grain structure including grain orientation, and the spatial distribution of the primary precipitates. The crack tip field in this three-dimensional volume element was then determined using the multiphysics simulation package DAMASK. A conventional phenomenological crystal plasticity constitutive law for face-centered cubic crystals was used to capture the behavior of the aluminum matrix, whereas linear-elastic material behavior was assumed for the precipitates. This analysis yields the stress-strain field in the vicinity of the crack tip as well as the amount of plastic deformation. The rotational part of the latter quantity can be compared directly to the grain misorientation measured in the EBSD analysis in the SEM, and is a good indicator of the most likely crack extension direction. It is shown that the characteristics of the crack tip field defined by grain rotation are in very good agreement with those of the crack paths found in the experiments.

12:10 **Fatigue endurance of aeronautical aluminum alloy 7075-T6, with artificial and induced pre-corrosion**

N. Gubeljak (Sp)[1]; .I.F. Zuniga Tello[2]; M. Milkovic[1]; G.M. Dominiguez Almaraz[2]
[1]University of Maribor (Slovenia); [2]Universidad Michoacana de San Nicolás de Hidalgo,, Morelia (Mexico)

Conventional and very high frequency fatigue tests were carried out on the AISI-SAE AA7075-T6 aluminum alloy, in order to evaluate the effect of artificial and induced pre-corrosion. Artificial pre-corrosion was obtained by two hemispherical pitting holes of 500 µm of diameter at the specimen center, machined and oriented following the longitudinal or transverse direction of the testing specimen. Induced pre-corrosion was achieved using the international norm ESA ECSS-Q-ST-70-37C of the European Space Agency. Specimens were tested under ultrasonic fatigue modality at frequency of 20 kHz, and under conventional fatigue modality at frequency of 20 Hz. The two applied load ratios were: R= -1 in ultrasonic fatigue tests and R=0.1 in conventional fatigue tests. Both testing devices used to perform the conventional and very high cycle fatigue tests were developed and constructed in our laboratories. The effects of artificial and induced pre-corrosion on fatigue endurance were addressed in the analysis of experimentally results, together with the surface roughness evolution before and after fatigue testing. Fatigue endurance was observed to decrease importantly with artificial and induced pre-corrosion. Finally, numerical investigations were carried out to assess the stress concentration associated with pre-corrosion pits, and the fracture surface of testing specimens were analyzed to identify the trends on cracks initiation and propagation.





14:50 **SIMULATION OF POROSITY FRACTIONS IN ALUMINUM CASTED STRUCTURE FOR AERO ENGINE APPLICATIONS**

G. Narayanan (Sp)[1]
[1]Rolls-Royce Deutschland Ltd & CO KG, Blankenfelde-Mahlow (Germany)

The simulation of casting process for bearing support structure and the material defect like porosity, distribution of porosity and volumetric porosity of the bearing structure is presented in this paper. The casting process has been iteratively simulated based on the pre designed casting parameters to forecast the real value of the porosity fractions. The finite element model of bearing support structure has also been simulated with GTN material model in order to compute the damage parameter over accumulated plastic strain with the predicted casting defects. The actual pore distributions on the bearing support structure are estimated from the real casting. The casting parameters are also be planned by iterative of casting simulations in order not to exceed the allowable casting defects. The simulated casting defects and casting parameters are also validated with real casting process. The simulated porosity fraction and actually obtained casting defects are well matched for the similar casting parameters.

15:10 **Near-threshold fatigue crack growth for the aluminum alloy EN AW 6082 at positive R-ratios**

T. Kirsten (Sp)[1]; M. Wicke[2]; F. Bülbül[3]; A. Brückner-Foit[2]; H.-J. Christ[3]; M. Zimmermann[1]
[1]Technische Universität Dresden (Germany); [2]University of Kassel (Germany); [3]University of Siegen (Germany)

To investigate the fatigue crack growth under VHCF relevant stress amplitudes high frequency testing equipment such as ultrasonic fatigue testing becomes essential. It allows the examination of long fatigue crack growth at a testing frequency of about 20 kHz. However, a quantitative description of the damage accumulation and crack growth data at such high frequencies is a true challenge. In order to gain insights into the barrier function of microstructural inhomogeneities such as large precipitates or grain boundaries, a direct correlation between local microstructure fatigue crack growth behavior has to be analyzed.
Previous investigations of the aluminum alloy EN-AW 6082 under tension-compression cycling (R = -1) have shown that especially the ferritic precipitates are influencing the crack growth rate despite the fact that the crack is in the long crack growth regime. Grain boundaries seem to have only a slight influence.
In the present study fatigue crack growth tests were performed at a stress ratio of R = 0.1. The aluminum alloy was examined in two different aging conditions (peak-aged and overaged). The cracks were initiated by means of a focused ion beam notch and a long distance microscope was used for in-situ observation of the crack growth. First of all the threshold was determined by means of the load shedding method. Then, crack growth was investigated at constant stress intensity factors close to the threshold. During the in-situ investigation a change in crack growth velocity can be detected. It is assumed that the barrier function of primary precipitates is again the major reason for crack growth retardation. The microstructural influence becomes more important with decreasing ΔK values, close to $\Delta K_{th}$ the primary precipitates can stop the crack growth entirely. Meanwhile the average crack growth rate decreases simultaneously with decreasing ΔK. But in comparison to the experiments under fully reversed loading the influence of the microstructure for the overaged condition seems already reduced when the applied stress intensity factor is 40 % above the threshold. For R = -1 an influence could still be seen at this ΔK range.

Session **Basic aspects**

11:10 **Influence of grain structure defects on fatigue strength in directionally solidified components studied by bi-crystal experiments and FEM**

M. Fried (Sp)[1]; N. Bellomo[1]; F. Vöse[1]; J. Albiez[1]
[1]MTU Aero Engines AG, Munich (Germany)

In directionally solidified components the optimum grain structure consists of columnar grains aligned parallel to the solidification axis. However, in real castings deviations may occur in various forms like e.g. transverse grains, high angle grains or separately nucleated grains. For life assessment of cast turbine components it is of high interest to quantify the impact of these defects on fatigue strength. Parts revealing typical grain deviations were investigated using metallography and EBSD to gather information on grain structure and crystallographic orientation. It was found that grain boundaries can be highly inclined to the solidification axis and grains can reveal a large misorientation with respect to <001>. Therefore, an impact on fatigue life can be expected due to limited strength of grain boundaries and stress concentrations arising from elastic misfit. In order to quantify those effects, fatigue experiments were carried out on nickel-based alloy M-247LC. Cylindrically shaped specimens were cut from bi-crystal plates, being produced by growing two crystal seeds with different orientation in parallel. The bi-crystal specimens were considered as a model material representing typical features of grain structure deviations, such as crystallographic misfit and inclination of the grain boundary with respect to the major loading axis. The fatigue life measured in LCF tests was found to be lower compared to a boundary free and <001> orientated single crystalline specimen. Subsequent to testing, the specimens were investigated using SEM and EBSD to specify the crack initiation and propagation mechanism as well as the defect size causing the failure. It was found that most of the cracks initiated close to the grain boundary, propagating into one of the grains. There was no evidence of low strength of the grain boundary itself. In order to predict the local stress distribution in the bi-crystal specimen and thus the location of failure, the crystallographic orientation measured in the two grains was incorporated into a finite element model. A crystal plasticity material model was applied to account for local plastic deformation. Finally, a non-local damage approach was used to predict fatigue life. The results were found to be in good agreement with the experiments. Thus, it could be shown that local stress concentration induced by the grain boundary and elastic misfit was the main driver for crack initiation and fatigue life of the specimens.

11:30 **A novel hybrid method to predict fatigue life and cyclic mechanical properties of materials**

H. Sajjad (Sp)[1]; H.u. Hassan[1]; M. Kuntz[2]; B.J. Schäfer[2]; P. Sonnweber-Ribic[2]; A. Hartmaier[1]
[1]Ruhr-Universität Bochum (Germany); [2]Robert Bosch GmbH, Renningen (Germany)

The application of instrumented indentation allows the identification of conventional material properties such as the elastic modulus and hardness. In the recent past, inverse methods have been developed, by which yield strength, work hardening rates, and tensile strength can be extracted from indentation experiments. However, determining material parameters for cyclic plasticity or fatigue strength still requires laborious and costly conventional fatigue experiments. In the current work, a novel hybrid method is presented that allows identifying material parameters for cyclic plasticity from cyclic indentation experiments by using a model-based inverse identification technique. To validate the method, it is applied to predict the uniaxial stress-strain hysteresis curve only from cyclic indentation results. The first test material has been quenched and tempered 50CrMo4 martensitic steel. The identified material parameters from cyclic indentation experiments predict cyclic uniaxial stress-strain behavior with a high accuracy with respect to the dissipated work per cycle between experimental and predicted values. The transferability of this novel hybrid method has been demonstrated by applying it also to soft technically pure copper, where also very good results have been achieved.





11:50 **Experimental evaluation of a critical plane model for multiaxial fatigue of metals containing small defects**

C. Bemfica (Sp)[1]; A. Dias[2]; R. da Costa[1]; F. Castro[1]
[1]University of Brasilia (Brazil); [2]Instituto Federal de Brasília, Brasilia (Brazil)

Fatigue limit data of 304L stainless steel and 1045 carbon steel are used to evaluate a recently developed critical plane model for multiaxial fatigue of metals containing small defects. The model is based on the square root of the area parameter and is designed to reflect the Mode I-dominated physical damage mechanism of small defects. The concept of directionally dependent fatigue strength is introduced to extend the critical plane definition to defects whose projected area varies with the plane. The Walker relation with a critical plane interpretation is proposed to account for the mean stress effect. The experiments were performed on specimens with small cylindrical holes under a variety of axial, torsional, and axial-torsional loading conditions, including the presence of mean or static stress. Different nonproportional loading paths were used to study the multiaxial fatigue behaviour. A detailed observation of the direction of the small cracks originated from the holes, at or just above the fatigue limit, was carried out. The model is found to give good estimates of both fatigue limits and crack directions.

12:10 **Fabrication of artificial defects to study internal fatigue crack propagation in metals**

A. Junet (Sp)[1]; A. Messager[2]; X. Boulnat[1]; J.-Y. Buffiere[1]; A. Weck[3]
[1]INSA-Lyon, Villeurbanne (France); [2]Arts et Metiers ParisTech, Bordeaux (France);
[3]University of Ottawa (Canada)

In several modern key industrial components (high speed train wheels, heart valves ...) cyclic loading occurs at very low stress levels which induce very long fatigue lives (NR larger than 109 cycles - the gigacycle regime). In this regime, component failure is predominantly caused by the initiation and the propagation of internal cracks. Experimental data on the growth of such cracks is still scarce at the moment, mainly due to experimental difficulties [HON][SER][YOS].
In this work, we present a method to produce fatigue samples with controlled internal defects which are used to induce internal crack initiation [JUN]. Diffusion bonding of thin metal sheets containing defects created by femto laser machining is used to produce sharp notches in the bulk of Ti-6Al-4V samples whose geometry and size enable to perform synchrotron tomography in situ fatigue tests. In situ experiments show that internal cracking systematically occurs at the notch. The propagation of those internal cracks is characterised in 3D. After approximately 50% of the fatigue life (for the stress level investigated) the cracks acquire a very regular quasi circular shape, which is typically observed for internal cracks. The da/dN - DK curves obtained are discussed with respect to crack growth data of the same material for tests performed in various environments. Different diffusion bonding environment conditions and thermal treatment are also tested and confirm the crucial role of the environment on internal crack growth.
This manufacturing method can be applied to other metals (cast iron, aluminium, etc.) but this presentation will focus on internal crack initiation in Ti-6Al-4V.

09:40 **Fatigue behaviour predicted based on metallographically determined inclusion size distributions**

J. Schumacher (Sp)[1]; B. Clausen[1]; H.-W. Zoch[1]
[1]Leibniz Institute for Materials Engineering - IWT, Bremen (Germany)

In steels, a cyclic loading below the yield strength can lead to failure. Cracks are formed on the surface or in the volume of components, propagate, and finally lead to the fracture of the specimen. In case of internal failures non-metallic inclusions often act as crack initiating sites. In this presentation a calculation approach for the fatigue strength of high strength steels based on non-metallic inclusions determined in microsections is introduced. The calculation approach consists of two parts. In the first step, the failure-critical defect is determined for the respective specimen or component geometry. In the second step, the fatigue strength of the specimen is calculated in dependence of the loading condition, steel grade and expected inclusion size. The determination of the inclusion size is based on metallographic investigations. Based on the ASTM 2283 standard, the distribution of the largest inclusions per metallographic section is determined. Various distribution functions are used to mathematically describe the distribution of the inclusions sizes. Depending on the specimen geometry and the loading condition, the failure-critical inclusion size is determined with aid of the distribution functions.
The fatigue strength prediction is based on a fracture mechanical approach. As described by Murakami [1], inclusions are regarded as cracks of the size of their cross sectional area perpendicular to the maximum principal stress. The calculation method takes into account the hardness of the steel, the inclusion size, local residual stresses, multi-axial load stresses and mean stresses. Various parameters are required to perform the calculation. For example, parameters which describe the threshold stress intensity factor range of small defects or material dependent parameters of fatigue criteria are required. Case hardened, quenched and tempered as well as bearing steels in different heat treatment conditions, which have been investigated in several research projects over the last two decades, are used as data basis for the parameter determination. By combining the inclusion size prediction with the fatigue strength calculation, it is possible to estimate the fatigue strength of different components on the basis of metallographic investigations.

10:00 **A multiaxial fatigue damage model for metals containing small defects**

F. Castro (Sp)[1]; E. Mamiya[1]; C. Bemfica[1]
[1]University of Brasilia (Brazil)

A critical plane model for the fatigue limit of metals with small defects is developed based on the square root of area parameter. The model is designed to reflect the Mode I-dominated physical damage mechanism of small defects. The concept of directionally dependent fatigue strength is introduced to extend the critical plane definition to defects whose projected area varies with the plane. The Walker relation with a critical plane interpretation is proposed to account for the mean stress effect. The model is evaluated using available experimental data of steels containing artificial surface defects and ductile cast iron having inherent graphite nodules. The experiments include different proportional and nonproportional axial-torsional loading conditions and defect types (cylindrical, hemispherical, and tilted hemiellipsoidal holes). The model is found to give good estimates of both fatigue limits and crack directions. A discussion on the physical interpretation of critical plane models in the context of the small defect fatigue problem is presented.





10:20 **Graphical method to asses the critical defect size of a linear indication found by UT/PAUT**

P. Deschênes (Sp)[1]; D. Thibault[1]
[1]Hydro-Québec, Varennes (Canada)

Prior to the exploitation of new or repaired turbine runners, Ultrasonic Testing (UT) or Phased Array Ultrasonic Testing (PAUT) are commonly used as inspection methods to ensure no critical defects are present in welded regions. This work presents a new methodology to assess the acceptability of linear indication measured by UT/PAUT. This method allows engineers and UT technicians to diagnose any linear indication found in the bulk using a colored contour map of the inspected section specifying the local maximum permissible size defect, 2c. It can be constructed using any kind of vector field and type of defects. This method applies the stress field of a particular section of the bulk on a typical defect found in the majority of fracture mechanics handbooks. Two major steps must be performed prior to calculate the map: 1-extraction of the stress distribution on a plane within the bulk from the FEA model and 2- calculation of the severity of the crack-like defect using a Kitagawa diagram for each node of the stress distribution previously extracted. From this information, one can draw a map of the critical crack-like defect that can be embedded in the bulk at node locations, taking into account the stress gradient, if there is any, the stress field, the distance between the surface and the threshold value. The figure 1, shows a typical representation of the map obtained: The method has been applied on the data collected during a turbine runner inspection. Both Hydro-Québec and GE collaborated during this investigation.

11:10 **Is fatigue failure predictable?**

A. Sendrowicz (Sp)[1]; A.O. Myhre[1]; S.W. Wierdak[1]; A. Vinogradov[1]; A. Weidner[2]; H. Biermann[2]; R. Mueller[2]
[1]Norwegian University of Science and Technology NTNU, Trondheim (Norway);
[2]Technische Universität Bergakademie Freiberg (Germany)

Over the past decades, fatigue crack growth has been an area of active research aimed at guided fatigue design on one hand and, on the other, at failure prediction in engineering facilities once the fatigue crack sets in. The former is footed primarily on the empiric Paris law relating the crack growth rate to the stress intensity ahead of the crack tip in the linear elastic fracture mechanics approximation. The latter therefore suffers from all limitations imposed by the Paris law or any of its modifications. The complexity of the mechanisms that govern the fatigue crack propagation calls for development of new physical models that capture the underlying physical mechanisms and microstructure evolution in the plastic zone and yet are robust and user-friendly enough to be applicable in engineering praxis. Having this as a main mindset and a future goal, we present the novel in-situ approach towards experimental investigation of the thermodynamics and kinetics of deformation processes in the plastic zone of the propagating fatigue crack in situ. We describe an original experimental setup including the synergy from the combined high-resolution infrared imaging, optical microscopy with digital image correlation and acoustic emission technique, and provide examples of its successful application to a set of stainless steels including the conventional hot-rolled stable 316L steels and metastable high-alloyed CrMnNi TRIP and TWIP steels.

11:30 **Crack to defect interactions in fatigue crack propagation accounting for elasto-viscoplastic behavior**

V. Maurel (Sp)[1]; S. Dezecot[2]; V. Chiaruttini[3]
[1]Mines ParisTech, PSL University, Evry (France); [2]EVATEC TOOLS, Lyon (France);
[3]ONERA, Chatillon (France)

For metallic alloys, most of the fatigue to defects interactions are analyzed considering high cycle fatigue conditions with lifing methodology at initiation. Recent progress for in situ observation of fatigue damage makes propagation analysis more accurate. This has been successfully applied for lost foam casting Al-alloys for low cycle fatigue condition using computed tomography (CT) experiments. CT has been used for both analyzing crack initiation and propagation from natural porous defects in situ at 250 °C [1] and for comprehensive study of standard fatigue crack growth tests using post-mortem observations [2].
The proposed paper deals first with a systematic measurement of morphology and location of defects interacting with the major crack during SENT fatigue crack propagation test achieved at 250 °C. Optical in situ observation yields surface crack to microcrack interaction measurements. CT has enabled in this case to derive associated geometrical criterion for crack to defect interaction for LCF condition.
Secondly, based on experimental observations, a systematic analysis of crack to idealized spherical defect has been achieved. This study is based on FEA, conform remeshing technique to model crack propagation, coalescence of cracks and elastoviscoplastic evaluation of mechanical state. G-theta method is used to evaluate FCGR in different geometrical configurations. This point yields an emphasis of the role crack closure associated to both strain localization and defects.
Finally, an explicit computation of realistic crack growth together with 3D mesh of the SENT specimen including meshing of defects has been developed. This helps for discussing the relative impact of different features described above in the crack to defect interaction for LCF loading.

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[2] Dezecot, et al. (2019), Materials Science and Engineering: A 743: 87-97.
[3] Abecassis, et al. (2019), International Journal of Fatigue, 118, 209-224.

Acknowledgements
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11:50 **Micromechanical modeling of fatigue damage initiating and propagating from 3D reconstructed microstructural defects**

A. Laukkanen (Sp)[1]; M. Lindroos[1]; T. Andersson[1]; T. Pinomaa[1]; J. Vaara[2]; A. Mantyla[2]; T. Frondelius[2]
[1]VTT Technical Research Centre of Finland Ltd, Espoo (Finland); [2]Wärtsilä, Vaasa (Finland)

The role of microstructural defects is critical for very-high cycle and ultra-high cycle fatigue (VHCF, UHCF). In high strength and purity steels for machine construction internal and surface penetrating inclusions are found to be common initiation sites, while for example in metal additive manufacturing prepared parts further pore and crack like defects are found to dominate the number of cycles to damage initiation and ultimately, to short crack growth and failure. In current work we present a fully damage coupled crystal plasticity based micromechanical model and methodology for evaluation of VHCF and UHCF behavior of metallic materials. To capture the damage accumulation process relevant for the respective micromechanisms of fatigue, we apply the approach to modeling of experimental test results where the microstructural models are created from data obtained by reconstructing fatigue damage initiation sites by way of focused ion-beam serial sectioning and x-ray tomography characterization. The results demonstrate what are the critical material features necessary to properly capture the underlying micromechanisms in defect containing metallic microstructures. Especially, the inclusion to microstructure interactions with respect to plastic slip and stress state in the adjacent metallic microstructure and the role of the interface imperfection are presented and discussed in detail. The approach yields results where the damage nucleation process can be captured by micromechanics and inferences with respect to VHCF and UHCF material performance can be made, also with respect to validation of the methodology. In addition to comparison of experimental and modeling results, coarse graining methods methods are discussed and addressed. The results provide a direct workflow how to develop, validate and exploit micromechanical methods to address fatigue associated engineering problems with far improved detail and accuracy of prediction than earlier.

14:10 **Searching for a reliable crack driving force parameter for various stress ratios under high-cycle fatigue in metals**

T. Vojtek (Sp)[1]; P. Pokorný[2]; T. Oplt[2]; L. Náhlík[2]; P. Hutar[2]
[1]Czech Academy of Sciences, Brno (Czech Republic); [2]Institute of Physics of Materials AS CR, Brno (Czech Republic)

Experimental data of crack growth rates for various steels were obtained in the near-threshold and the Paris regime at stress ratios with the presence of crack closure (R = 0.1 and R = –1) and for the closure-free stress ratio R = 0.8. Crack closure levels Kcl were derived from the differences between these two curves. The results were much different from the crack closure values computed by the commonly used models by Newman and by finite element analysis even in the Paris regime, where crack closure is usually supposed to be well predicted. The crack driving force in terms of ΔKeff = Kmax – Kcl could not explain behaviour of the investigated materials. Various studied effects (material model, possible violation of small-scale yielding or the effect of specimen thickness) could not explain the differences either. It is unclear whether the intrinsic or the extrinsic resistance to crack propagation was responsible. It means that alternative crack driving force parameters need to be found. Possible ways of finding such parameters will be discussed. Numerical modelling also revealed incorrectness of the commonly used ratio between plastic zone sizes at the free surface and in the middle section of the specimen. It was only about 1.3, in contrast to the classical value of 3.

Session **Cast iron and cast steel**

14:10 **Notch fatigue and crack growth resistance of ferritic and pearlitic ductile cast iron**

M. Dallago (Sp)[1]; D. Lusuardi[2]; V. Fontanari[1]; M. Benedetti[1]
[1]University of Trento, Povo (Italy); [2]Fonderie Ariotti SpA, Adro (BS) (Italy)

Ductile cast iron (DCI), due to its good static mechanical properties achievable thanks to the improvements in casting technology, is becoming a viable alternative to steel in many structural components, such as crankshafts, wind turbine parts, pipes, pumps. Moreover, compared to steel, DCI is easier to cast in complex shapes, it is less dense and can meet the mechanical requirements without expensive heat treatments. Many of the applications where DCI is a possible replacement for steel involve cyclic loads. Unfortunately, the fatigue properties of cast iron are generally inferior to those of steel due to the peculiar microstructure of DCI, characterized by the presence of graphite and various types of casting defects such as shrinkage porosity and inclusions and other impurities that act as stress concentrators. In addition, the wide variability in the morphology of these defects translates into a wide scatter in fatigue strength data that negatively affects the mechanical reliability of cast iron parts. Many practical engineering components typically present notches and grooves that locally intensify stresses and that need to be accounted for in the prediction of fatigue life. In other words, when designing mechanical components in DCI, both the effects of the peculiar microstructure and of the geometry should be considered. Unfortunately, till today reliable design criteria for notched DCI members are not available. A promising approach for the prediction of the notch and defect sensitivity of the fatigue limit is the theory of critical distances.
The aim of this work is to investigate the applicability of the theory of critical distances to ferritic and pearlitic ductile cast irons. The critical length parameter is estimated from fully reversed fatigue tests carried out on plain and notched specimens designed to maximize the stress gradient at the notch. The influence of the defects (shrinkage pores) and of the graphite particles on the fatigue limit of the plain specimens is estimated with the Murakami √area model. The critical distance parameter estimated with such procedure is then compared with that obtained using the threshold stress intensity factor range measured from crack growth tests.





14:30 **Damage parameter based fatigue assessment of cast steel components containing internal defects**

M. Jung (Sp)[1]; S. Nagel[2]; C. Rauber[3]; E.P. Toma[3]; M. Farajian[1]; K. Szielasko[3]; T. Ummenhofer[2]
[1]Fraunhofer Institute for Mechanics of Materials IWM, Freiburg im Breisgau (Germany); [2]Karlsruhe Institute of Technology (KIT) (Germany); [3]Fraunhofer Institute for Nondestructive Testing IZFP, Saarbrücken (Germany)

In steel constructions, components from cast steel are attractive alternatives to complexly formed weldments. However, depending on the geometry and the casting process internal defects such as pores or inclusions cannot be fully avoided. Under fatigue loading, such defects could act as -crack initiation sites, which lead to crack initiation and finally to failure of a component. For the fatigue assessment of the manufacturing-related internal defects in cast steel suitable engineering rules are still missing. This in turn leads to the extreme consequence that expensive components have to be discarded.
In the present work, the influence of manufacturing-related internal defects on the fatigue strength of components is investigated and engineering assessment procedures are validated and recommended.
Specimens from G20Mn5 and G22NiMoCr5-6 cast steel are manufactured using a special mold geometry to control the formation of internal defects. The specimens are examined by CT measurements to get a 3D representation of the defect shapes and distribution. The fatigue life of the specimen is determined by cyclic testing at various load levels. To employ fatigue assessment different modelling approaches are tested and evaluated with regard to their applicability, with a spotlight on the utilization of damage parameters to assess crack initiation life. The underlying material models are adjusted to experiments on nearly defect free material.
The experiments on specimen containing defects show a strong correlation between fatigue life and defect size and position. As expected, fully internal defects are less damaging than surface and subsurface defects -. For an efficient calculation of the damage parameters in a finite element model it proves to be suitable to consider the inner defects by using a porosity dependent material model. Based on the stress-strain field at the boundaries of the pores the damage parameter can be determined as measure for crack initiation, which conservatively describes the fatigue life. The damage parameter according to Fatemi and Socie was proven as a suitable parameter for the lifetime assessment of castings with internal defects.

14:50 **Correlating fatigue properties and microstructural defects of high strength thick-walled nodular cast iron components**

J. Lohmiller (Sp)[1]; J. Hoffmeister[1]; J. Hermes[1]
[1]SEW-Eurodrive GmbH & Co. KG, Bruchsal (Germany)

Nodular cast iron materials are attractive for thick-walled and highly stressed gear components due to the possibility to design complex structures requiring a combination of high strength and moderate ductility. In order to max out the potential of these materials, an in-depth characterization of their fatigue properties is necessary. This allows for reduced safety margins.
In this study, austempered ductile iron (ADI) EN-GJS-900-8 and conventional nodular graphite iron EN-GJS-700-2 were developed and optimized for industrial planetary carriers with shaft diameters ranging from 120 mm to 460 mm. Both materials have been cast into the same patterns of differently sized planetary carriers. Fatigue specimens were prepared from the cast components and tested in order to determine the fatigue limit. Microstructural characterization and fractography including optical and scanning electron microscopy were carried out.
As a result, the correlation between mechanical and microstructural properties reveals the importance of fine and nodular graphite accompanied by the absence of micro porosities or other casting defects. A scaling behavior was developed in order to estimate fatigue strength based on the maximum defect size in the tested volume. Moreover, a minor influence of matrix structure embedding the graphite - pearlitic or ausferritic - was determined.
According to the results obtained, the fatigue strength of conventional high strength cast iron may be adequate by improving graphite quality and eliminating casting defects. Thus, the accurate design process of a cast component is essential to avoid an increase of alloying elements and the expansive heat treatment in salt bath necessary for ADI. By understanding the correlations between mechanical properties of nodular cast iron and its microstructure, the efficiency of cast components can be enhanced, while costs can be reduced.

15:10 **Effect of defects on the fatigue crack initiation strength of ferrite-pearlitic nodular cast iron test specimens and components**

M. Gróza (Sp)[1]; Y. Nadot[2]; K. Váradi[1]
[1]Budapest University of Technology and Economics (Hungary); [2]Institut Pprime, ISAE-ENSMA, Poitiers (France)

The study investigates the defect influenced fatigue on the example of complex industrial components. The phenomenon is analysed through fatigue testing and fracture surface analysis complemented with simulations based on the Finite Element (FE) Method and the evaluation of the local cyclic stress state with the Defect Stress Gradient Approach [1,2].
With the comparison of computation with experimental results for artificial and natural defects at specimen and component scales, conclusions are drawn with scientific and practical consequences. The Defect Stress Gradient approach is applied to evaluate the local stress state computed by elasto-plastic and linear elastic FE-calculations or estimated by the simplified technique proposed in [2]. The calculation based on the elastoplastic stress-state with the simulation of the load cycles and consideration of the cyclic nonlinear kinematic hardening behaviour leads to a precise assessment of the fatigue strength of test specimens and components with artificial defects having various shapes. Utilizing a simplified estimation for the stress concentration factors leads to a directly expressable allowable defect size, which can be plotted as an FE-result field and used effectively for the quality control process of safety critical castings.





16:40 **Microstructure and Fatigue of G20Mn5 Cast Steel**

A. Bermond (Sp)[1]; J.-F. Carton[2]; M. Lenci[1]; J. Stolarz[1]; H. Klocker[1]; C. Roume[1]
[1]MINES Saint-Étienne (France); [2]CastMetal, Feurs (France)

Cast steels, commonly used in structural and safety parts for different applications (e.g. trains, building machines or excavators), undergo severe cyclic loadings. Cast microstructures exhibit a variety of defects depending on the foundry process and the particular component geometry. Present work analyzes the relation between post casting heat treatment and fatigue life of G20Mn5 cast steel. G20Mn5 steel grade ingots (300x100x100 mm) were cast at Castmetal Feurs foundry (Loire – France). These ingot dimensions allow for a significant microstructure gradient. Ingots were submitted to two post casting heat treatements: normalization or quenching and tempering.
First, the microstructure was characterized by optical light and SEM observations for both heat treatments. The variation of the microstructure within the ingot volume has been quantified. Mechanical test samples (monotonic and fatigue) were cut in the center and the outer area of the ingots. Shrinkage porosity controls fatigue life at the first order for both heat treatments. The variation of this porosity in the ingot volume was quantified for both heat treatments. The porosity increases from the ingot surface to the center. The correlation between void volume fraction and fatigue life was determined for both heat treatments.

17:00 **Microstructure based fatigue strength prediction of ductile cast iron with the shakedown theorem**

C. Gebhardt (Sp)[1]; C. Broeckmann[1]; A. Bezold[1]
[1]RWTH Aachen University (Germany)

Fatigue in metals is determined by size and shape of defects or non-metallic inclusions. Fatigue strength predictions can be made using micromechanical simulations with the shakedown theorem. In these simulations a good geometrical representation of defects is mandatory since they cause high local stresses. An advanced method based on micrographs is presented to study the influence of inclusions and defects on fatigue strength and development of cyclic plasticity in ductile cast iron (DCI). In DCI, the graphite nodules influence the development of cyclic plasticity in the high cycle fatigue regime, eventually leading to microstructural damage and fatigue crack growth. A modelling technique to reconstruct graphite nodule geometries out of low-resolution micrographs is presented. The static shakedown theorem is applied to the micromechanical models to calculate the lower bound of the fatigue strength. The influence of graphite morphologies on the fatigue strength is analyzed based on a number of micrographs. The results are compared to experimentally determined SN-curves with varying graphite morphologies, and the fatigue damage mechanisms are analyzed with SEM and EBSD. Results show a significant influence of both size and shape of graphite nodules on the development of cyclic plasticity and microcrack formation.

17:20 **Cyclic R-curve measurements in nodular cast iron**

L. Patriarca (Sp)[1]; A. Pourheidar[1]; S. Beretta[1]; M. Cova[2]
[1]Politecnico di Milano (Italy); [2]SACMI Imola S.C. (Italy)

The fatigue life of nodular cast iron is profoundly influenced by the growth of fatigue cracks from porosity generated by the casting process. According to the application of hydraulic presses, the crack growth might occur under negative load ratio. In this scenario, the initial stage of crack propagation is governed by the development of crack closure which determines a strong crack threshold dependence with the crack length. Consequently, it is of fundamental importance the proper measurement of the so-called cyclic R-curve which defines the change of the crack threshold as the crack advances from the porosity with limited initial crack closure to a steady-state condition where the combined effect of plasticity-induced, roughness, oxidation crack closure yield a higher crack threshold. In this study, the cyclic R-curve is measured from experiments employing micro-notched specimens for three stress ratios R: 0, -1 and -2.5. Following pre-cracking in compression to minimize the load history effects, the crack is subjected to block of cycles at constant DK in order to induce an initial crack advancement and a successive crack arrest due to the crack closure development. The Digital Image Correlation technique was employed to precisely pinpoint the crack opening and closing and to measure the crack advancements. The study points to discuss for the cast iron under investigation the possible application of the R-curve to estimate the Kitagawa-Takahashi diagram which defines the change of the fatigue strength with the crack size.

17:40 **Detection and understanding of the chunky graphite degeneration in ferritic spheroidal graphite cast iron materials (SGI) with respect to fatigue – results of a recent comprehensive review**

W. Baer (Sp)[1]
[1]Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin (Germany)

Ferritic spheroidal graphite cast iron materials have gained a remarkable technical potential and economic impact in modern industry. These features are closely related to the question of how the cast materials can be produced without structural defects and graphite degenerations among which chunky graphite is considered most evil. Although the chunky graphite degeneration superficially seems to be well known, its metallurgical background is still controversially discussed, appropriate field-tested nondestructive tools for its quantification in castings are lacking, and the knowledge on its impact on material properties is rather limited. Addressing this status, a comprehensive overview on the subject has been compiled by the author recently [IJMC2019] considering formation and growth mechanisms, metallurgical aspects of appearance and prevention, and with special attention to microstructural characterization and impact on properties.
The present contribution is focused on how to properly understand the specific morphology of chunky graphite and its impact on the fracture behavior under fatigue loading conditions. Challenges and possibilities of the experimental microstructural characterization using destructive and nondestructive techniques are discussed. Special emphasis is laid on the impact of chunky graphite on fatigue properties such as fatigue limit and fatigue crack growth rate of ferritic SGI materials based on available experimental data. Moreover, conclusions for the assessment of castings affected by chunky graphite are drawn.





Session **Fracture mechanics**

16:40 **Influence of type of loading and interference levels on the stress intensity factor for a crack emanating from a hole**

R. Prakash (Sp)[1]; K. Hithedra[1]
[1]Indian Institute of Technology Madras, Chennai (India)

Pin loaded lugs, rivet joints and bolted joints are indispensable elements of a structure in any industry. During service, these components undergo dynamic loading, resulting in fatigue failure. Several theoretical, experimental and numerical studies have been carried out to estimate stress intensity factors and fatigue lives in pin loaded lugs, rivet joints and bolted joints. Many of the previous studies do not address the combined effect of loading type and specimen geometry to arrive at SIF. This study using Finite Element analysis, considers a rectangular plate with cracked hole to derive the stress intensity factor for a through-the-thickness crack for the following load cases: a) Direct loading- open hole configuration, b) Bearing load –cosine distribution, c) Pin load without interference, d) Pin load with various levels of interference with plate, e) Pin load with a bush interference with plate and no interference between pin and bush and f) Pin load with the size of pin equivalent to the bush.

Conclusions:

1) Irrespective of the type of loading, as the crack length increases, the SIF values converge up to 1% interference levels at 2a/W=0.73.
2) In case of pin load, for interference levels up to 0.5%, beyond 2a/W=0.33, there is no significant variation in the SIF values.
3) Beyond the threshold interference level of 0.5% between plate and pin, for all crack lengths, SIF increases with increase in interference levels.
4) Below the threshold interference limit, at each interference level, there exists a crack length beyond which the interference results in increase in SIF rather than reducing it.
5) The use of a bush along with pin is beneficial in reducing the SIF up to a transition value of 2a/W, ranging between 0.2 to 0.3. This is valid at all interference levels studied, except at 0.25% interference where, beyond 2a/W=0.33, there is no difference in SIF values between the two cases.
6) The pattern of variation of SIF is similar for both the cases of Bush interference and equivalent pin interference.
7) At lower interference levels, up to 0.25%, at all crack lengths, although bush interference yielded slightly higher SIF than the equivalent pin interference, at 0.5% level and higher levels, bush yielded lower SIF values compared to equivalent pin.
8) After certain crack length and certain interference levels, positive effects induced by interference are nullified by the geometrical effects.

17:20 **Reduced models for the rapid evaluation of stress intensity factor and j–integral in structures containing defects**

H. Launay (Sp)[1]; J. Besson[1]; D. Ryckelynck[1]; F. Willot[1]
[1]Mines ParisTech, PSL University, Evry (France)

Widely-used in industry, pipeline structures might contain defects (cavities, cracks) which can be generate during fabrication, handling, girth-welding, or year-long operations. Their replacement is complex and expensive, therefore it is important to determine critical and non-critical defects. Pipelines indeed undergo internal pressure cycles so that defects such as cracks may propagate therefore affecting their lifetime.
This study is part of a larger work aiming at estimating global fracture parameters in components such as the stress intensity factors as well as the J–integral. It is common to address this problem using charts or simplified formulas that enable to quickly estimate stress intensity factors in structures containing cracks (Zerbst et al, 2007). Nevertheless those charts only deal with standard crack configurations and the interaction between cracks is rarely taken into account. A higher accuracy is indeed obtained using full-field finite element computations which however are very time consuming in particular if plasticity needs to be accounted for. To achieve both accuracy and fast response, it is proposed in this work to use a hyper-reduction method which has shown considerable speed improvement in plasticity (Ryckelynck et al, 2015).
The method allows describing structures and defects separately owing to their different sizes. Reduced basis are first created for both uncracked structures and defects. Multiscale construction techniques are then used to rapidly obtain solutions for cracked structure in the context of small deformations (Lacourt,2019). The technique thus allows (re)using crack databases on various structure. The new method is applied to a straight pipe containing various cracks. Results are compared to both full finite element simulations and known reference solutions. More complex cases for which no simple solutions exit, such as dissymmetric cracks, non-planar cracks or cracks with wavy front, are also investigated.

17:40 **Kitagawa-Takahashi diagram for real defects: the role of local matrix and secondary cracks**

M. Cova (Sp)[1]; F. La Donna[1]; P. Negrini[2]; R. Rizzoni[2]; P. Livieri[2]; R. Tovo[2]
[1]SACMI S.C., Imola (Italy); [2]University of Ferrara (Italy)

This work focuses on the applicability of the Kitagawa-Takahashi diagram on real defects’ experimental data gained by crossing axial fatigue testing, computed tomography, 3D metrology and optical microscopy.
Solidification shrinkages and degenerated graphite clusters are detected using computed tomography on samples taken from core areas of heavy-walled spheroidal cast iron castings. Following Murakami’s approach, each defect is described by its projected area and a different shape factor for surface and internal defects. A fatigue limit is associated with each of them, using an El-Haddad formulation, and the defects are then ranked. The samples are fatigue tested and the killer defect is identified among all others. Subsequently, optical microscopy analysis is performed on the killer and a selection of the most critical defects. Local matrix phases and short crack presence are assessed. Most critical defects show some degree of crack initiation and propagation. The results allow a better understanding of the real defects’ behavior and the validity of the model.





16:40 **A NOVEL ANALYSIS OF STRESS INTENSITY FACTORS OF DISTRIBUTED NON-PLANAR SURFACE CRACKS AND ITS APPLICATION TO CORROSION FATIGUE PROBLEM.**

A. Abass (Sp)[1]; H. Matsunaga[1]
[1]Kyushu University, Fukuoka (Japan)

This paper focused on numerical analysis of Mode I Stress Intensity Factor, KI, of multiple non-planar semi-elliptical cracks that are distributed on the surface on a semi-infinite body under tension. Emphasis was placed on the nature of the interaction among cracks in close proximity. The analysis was based on the technique of Distributed Dislocation Method (DDM), which is an eigenstrain method. The eigenstrain element was developed from the stresses produced by an infinitesimal dislocation loop in a semi-infinite body. Difference between results of two interacting surface cracks in this work was always smaller than 2% when compared with reported results from earlier researcher. Furthermore, due to the adopted numerical integration methods and meshing procedure, solution of 100 distributed cracks was obtained within approximately 15 min when performed on a typical personal computer, i.e., solution for a single crack took less than 10 s. In addition, in the manuscript, practical application of this method to corrosion fatigue problem and material quality control will be proposed.

Session **Non-destructive testing and scatter**

09:40 **Internal fatigue crack investigation by in-situ synchrotron micro-tomography**

A. Messager (Sp)[1]; A. Junet[2]; T. Palin-Luc[3]; J.-Y. Buffière[2]; N. Saintier[3]; N. Ranc[3]; M. El May[3]; W. Ludwig[4]; J. Lachambre[2]; Y. Gaillard[5]; Y. Nadot[3]
[1]University of Bordeaux, Talence (France); [2]INSA-Lyon (France);
[3]Institut Pprime, ISAE-ENSMA, Bordeaux (France); [4]ESRF, Grenoble (France); [5]CTIF, Sèvres (France)

Defects are natural stress concentrators and constitute as such a major cause of fatigue failure in cast aluminium alloys. Most of existing studies focus their efforts on fatigue crack initiating from surface defects as they have been shown to be the most deleterious ones in High Cycle Fatigue (HCF) regime. However in Very High Cycle Fatigue (VHCF), internal crack initiation dominate. Only a few studies on internal fatigue cracks have been published [1, 2]. The aim of this work is to study internal fatigue crack propagation mechanisms and kinetics by the use of in-situ synchrotron micro-tomography fatigue tests. To promote controlled internal crack initiation, specimens containing an internal casting defect artificially introduced are tested at very low stress amplitudes in the VHCF regime. A new and unique ultrasonic (20 kHz) fatigue testing machine was developed in order to perform in-situ synchrotron fatigue tests [3]. This machine is instrumented with real time modal analysis [4] and infrared thermographic [5] measurement devices to automatically detect crack initiation. The crack propagation mechanisms show strong interactions between the crack path and the microstructure which is analysed using both diffraction contrast tomography [6] and EBSD microscopy analysis. Internal crack propagation kinetics are compared to reference crack propagation data resulting from propagation tests at 20 kHz.

10:00 **SteBLife - short-time fatigue life evaluation by taking advantage of NDT measurement techniques**

H. Wu (Sp)[1]; Z. Teng[1]; C. Boller[1]; P. Starke[2]
[1]Saarland University, Saarbrücken (Germany); [2]Hochschule Kaiserslautern (Germany)

The comprehensive understanding of fatigue mechanisms and damage evolution processes of metallic materials requires a reliable characterization of the microstructure, which changes steadily due to the applied cyclic loading during fatigue processes. Since the linear damage accumulation models cannot fully represent the realistic cases, it is expected, that the advanced fatigue life evaluation methods should provide more fatigue parameters than by conventional methods.
In this regard, different short-time procedures have been developed during the last years by the authors by taking the fact into account, that the nonlinearity of the elastic-plastic behaviour of metallic materials could be characterized more appropriately by combining the non-destructive testing (NDT) methods and the digitalization of the measurement as well as signal processing techniques. Thus, the improved gain from fatigue data can be used to reduce the experimental effort and costs significantly.
SteBLife is one of these new short-time methods showing new possibilities in rapid fatigue data evaluation, whereby only three to five tests are required to determine a complete S-N-curve including mean and/or complete scatter bands. If just a trend S-N-curve is desirable, the number of tests could even be reduced down to one single test.
Beside the reduction in time and cost for experimentation, SteBLife offers also the possibility to take advantage of the diverse fatigue-related parameters, in order to transform potentially the traditional S-N-curves into multidimensional datasets to be used as input for different structural simulation or assessment tasks.





10:20 **Finite Element analysis of dissimilar aluminium weldings based on X-ray computed tomography and instrumented indentation data.**

F. Teichmann (Sp)[1]; A. Ziemer[1]; J. Hensel[1]; K. Dilger[1]
[1]TU Braunschweig (Germany)

In welded structures made from Aluminium wrought and high pressure die casting alloys, different defects related to welding can occur. Aluminium wrought alloys tend to exhibit heat cracking phenomena as well as a degradation of the heat affected zone (HAZ), whereas Aluminium cast alloys predominantly show weld porosity and incomplete fusion defects. When welding Aluminium wrought alloys to Aluminium cast alloys, the risk of heat cracking is significantly reduced due to the Silicon and Magnesium content of the cast alloy. However, the occurrence of various irregularities, such as porosity, incomplete fusion, surface irregularities and the degradation of the HAZ depends on the welding process, the process parameters, the composition the aluminium alloy as well as on the casting process.
Aiming to describe the behaviour of these geometrical defects and the metallurgical condition of dissimilar Aluminium weldings under static loading, the following approach is undertaken within the current study: Firstly, tensile test specimen and metallurgic cross sections are taken from various weldments. Secondly, the tensile testing probes are investigated by the use of X-ray computed tomography (XCT) and the cross sections by instrumented indentation testing (IIT). In a next step, XCT voxel data is converted into a tetrahedral FE mesh containing regions of differing material laws based on the outcome of the IIT. Afterwards, a numerical FE simulation of the tensile test is carried out using the created meshes of the test specimens, which include all detected irregularities. Subsequently, a tensile test is performed on the physical test probe and the results of simulation and experiment are compared. Based on the results the behaviour of the different welding defects under static loading is discussed.

11:30 **The defect acceptance approach to the fatigue degradation based on X-ray tomography and machine learning**

S. Wu (Sp)[1]; H. Bao[1]; Y. Hu[1]; X. Peng[1]; Z. Wu[1]; G. Kang[1]; T. Burnett[2]; H. Zhang[3]; P. Withers[2]
[1]Southwest Jiaotong University, Chengdu (China); [2]The University of Manchester (United Kingdom);
[3]Huazhong University of Science and Technology, Wuhan (China)

The defects introduced by additive manufacturing (AM) are deemed as an essential factor to determine the service performance of near-net-shape metallic components since these defects can act as the stress concentrator and resultant crack initiator. Together with traditional post-mortem fatigue experiments on AMed specimens, high-resolution synchrotron radiation and microfocus X-ray computed tomography was also collaboratively employed to acquire rich defect data in three dimensions and to feed the subsequent probabilistic statistical model. In this respect, the support vector machine (SVM), a well-defined machine learning (ML) model, was particularly selected to perform the regression analysis on defects and experimental lifetime for the service performance assessment. The location, morphology, dimension, population and coupled effect on the fatigue degradation level were quantitatively characterized by using machine learning. This work can provide a significant reference for integrity structural assessment of AMed metal parts.

11:50 **LIMIT: probabilistic platform for fatigue assessment**

M. Cova (Sp)[1]; R. Cenni[1]; G. Puccetti[1]; S. Romano[2]; S. Beretta[2]
[1]SACMI S.C., Imola (Italy); [2]Politecnico di Milano (Italy)

LIMIT is an in-house, phyton-based fatigue assessment software seamlessly connected to the FEM solver. The presentation is focused on the defect-based approach module.

Main features:
1. fatigue strength defined by K-T diagram, El-Haddad and Murakami formulation
2. defect population defined by statistics of extremes
3. designed for a non-specialist user, for either the design or quality control phase

Unique features:
4. defect population is a local information and can be different for each node.
5. defect population can be derived directly from a manufacturing simulation (e.g.: casting process)
6. statistical size effect is considered

Emphasis will be given on the interconnections between the manufacturing process and the defect population(s).

12:10 **A new software for the estimation of the P-S-N curves in presence of defects: statistical models and parameter estimation**

A. Tridello (Sp)[1]; D.S. Paolino[1]
[1]Politecnico di Torino (Italy)

It is well known in the literature that fatigue failures originate from the weakest element within the component risk-volume (i.e., the region of material subjected to a stress amplitude close the maximum applied stress). In particular, for metallic materials the fatigue crack typically originates from the most critical surface defect in the High Cycle Fatigue (HCF) region; whereas, it generally originates from the most critical internal defect in the Very High Cycle Fatigue (VHCF), at stress amplitudes below the so-called 'transition stress amplitude'. Since the fatigue crack originates from critical defects, the P-S-N curve must necessarily take into account the random distribution of critical defect size. However, in the literature, there are few statistical models capable of modelling the dependency between the fatigue life and the defect size or taking into account the presence of different failure mechanisms (e.g., surface crack nucleation in HCF and internal crack nucleation with fish-eye morphology in VHCF region).
In the present paper, a new software for the estimation of the P-S-N curves is proposed. The statistical P-S-N models that have been recently proposed by the Authors are considered in the software and described in the paper. The procedure for the parameter estimation is also explained in detail: both the least square method and the maximum likelihood principle are implemented, depending on the presence of runout specimens. The software is finally validated with simulated datasets and with experimental datasets taken by the Authors or available in the literature.





Session **Special applications**

14:10 **Capabilities of metal magnetic memory method for quality control of engineering products**

An. Dubov (Sp)[1]; Al. Dubov[1]; S. Kolokolnikov[1]
[1]Energodiagnostika Co. Ltd., Reutov (Russia)

It is known that the main sources of damage during operation of engineering products are local stress concentration zones (SCZs) that are formed under the action of workloads primarily on defects of metallurgical and process nature.
Metallurgical and process manufacturing defects are known to cause high level of residual stresses (RS) in local zones of the product. RS control at some productions is performed on a selective basis. In this case the average (volumetric) level of RS is inspected, and local RS zones due to internal defects of the metal, as a rule, are not inspected and omitted. Besides, the location of these local zones and the method of their detection are unknown.
As a rule, RS control during the incoming inspection is not performed. For these reasons, during the very first years of products operation under the working load their "rejection" takes place. Process and metallurgical defects, causing the high level of RS in local zones of products, at unfavorable combinations with stresses due to working loads cause accelerated development of damages.
At present the products inspection at manufacturing plants and during operation consists in the usual flaw detection without any assessment of stress concentration level on apparent (discontinuity flaws) and implicit (structural) defects.
The metal magnetic memory (MMM) method developed by Energodiagnostika Co. Ltd. (Moscow) becomes more practically implemented for solution of the problem of determination of local SCZs in new and operated products. Russian and International standards on the MMM method are published.
The paper considers the capabilities of the MMM method during the diagnostics of new and operated products in order to detect local SCZs – the sources of damages development. Examples of control of fatigue development and material defects are shown.

14:30 **High heat flux fatigue and defect features of fusion reactor components**

J. You (Sp)[1]; E. Visca[2]; H. Greuner[1]; S. Roccella[2]; M. Richou[3]; M. Fursdon[4]; A. von Müller[1]; G. Dose[5]
[1]Max Planck Institute for Plasma Physics, Garching (Germany); [2]ENEA, Frascati (Italy);
[3]CEA, Cadarache (France); [4]CCFE, Culham (United Kingdom); [5]Tor Vergata University of Rome (Italy)

One of the major R&D focuses in the European fusion power plant (DEMO) program is to establish a physical as well as technological basis for reliable power exhaust during normal and off-normal operational scenarios. In this regard, the most crucial engineering challenge is to develop robust high-heat-flux components (such as divertor targets) being capable of withstanding extreme thermal loads up to 20MW/m2 with a sufficient heat removal capacity and structural reliability. Moreover, to maintain structural integrity and reliability under intense fast neutron irradiation and to ensure sufficient lifetime against armor erosion and cooling pipe corrosion are further critical requirements.
In the framework of EUROfusion DEMO divertor project (WPDIV), integrated R&D efforts have been conducted to develop advanced design concepts and related key technologies for the divertor targets. Emphasis is placed on the experimental demonstration of envisaged high-heat-flux fatigue performance of the novel design concepts using small scale mock-ups. To this end, dedicated test mock-ups were manufactured on the basis of extensive design studies, non-destructive inspection techniques were employed to detect defects included during production, high-heat-flux fatigue tests were conducted by means of neutral beam irradiation and microscopic post-examination was carried out for damage characterization. Finally, FEM-based failure modelling was performed to support the interpretation of damage and failure features observed in the mock-up testing.
In this contribution, a brief overview is presented on the major engineering issues and R&D activities for the high-heat-flux components of fusion reactors, defect inspection methodology and the selected results of the latest high-heat-flux test campaign.

14:50 **Investigation of rolling contact fatigue crack initiation from non-metallic inclusions in bearings**

G. Ravi (Sp)[1]; K. Nikolic[1]; W. De Waele[1]; R. Petrov[1]; K. Verbeken[1]; S. Hertelé[1]
[1]Ghent University, Gent (Belgium)

Offshore wind turbine bearings operate in harsh working conditions and may fail prematurely due to rolling contact fatigue (RCF). The microstructural changes associated with RCF are often reported as (i) butterfly wing formation around non-metallic inclusions, (ii) dark etching areas, and (iii) white etching cracking (WEC). Understanding these premature failures requires the study of RCF at multiple scales (macroscopic, microstructural) and stages (crack initiation and propagation). This paper presents a finite element (FE) modelling approach to evaluate RCF crack initiation originating from the inclusions. A submodel containing an inclusion is derived from the global FE model of a rolling contact. Moving Hertzian load is simulated to mimic the rolling pass and the stress history around the inclusion/matrix interface is adopted within Fatemi-Socie (F-S) critical plane approach to calculate fatigue damage. The model is coupled with an experimental statistical distribution of inclusions (type, size, and location), leading to macroscopic failure prediction. Investigating the link between RCF and white etching cracks is ongoing.

15:10 **Material and fatigue investigation of a white etching crack on a marine bevel gear**

S. Böhme (Sp)[1]; A. Vinogradov[1]; V. Olden[2]; M.L. Nedreberg[3]
[1]Norwegian University of Science and Technology NTNU, Trondheim (Norway);
[2]Sintef Industry, Trondheim (Norway); [3]Kongsberg Maritime CM AS, Ulsteinvik (Norway)

The microstructure of a white etching area around a subsurface crack on a marine bevel gear was studied by means of light microscopy, scanning electron microscopy, transmission electron microscopy and atom probe tomography. The material shows clear signs of recrystallization in a 20 µm band around the crack with grain sizes in the area of 10-20 nm. Using electron diffraction and atom probe tomography, the phase of the nanocrystalline material was determined to be ferrite with visible Nickel segregations on the grain boundaries.
To support the material investigation, hardness and hydrogen measurements and multiaxial fatigue analysis of the gear tooth were carried to understand the risk of subsurface cracking.





09:40 **Characteristics of plastic deformation and strain gradient associated with hydrogen-induced delayed crack propagation in a single-crystalline Fe-Si alloy**

T. Huynh (Sp)[1]; M. Koyama[2]; Y. Takahashi[3]; S. Hamada[1]; K. Tsuzaki[1]; H. Noguchi[1]
[1]Kyushu University, Fukuoka (Japan); [2]Tohoku University, Sendai City (Japan);
[3]Kansai University, Osaka (Japan)

A delayed crack propagation test using a thin sheet specimen of a single-crystalline Fe-3wt%Si alloy under constant load in a hydrogen environment was performed. A rectangular specimen (90 × 30 mm) was prepared from a sheet of material (thickness = 0.18 mm) with a (110) surface. A through-notch was introduced along the $[1\bar{1}0]$ direction at the center of the specimen, and a fatigue pre-crack was then introduced on the (001) plane from the notch root (total crack length was 1.18 mm). An electro-hydraulic testing machine was used to conduct the test. A sustained load of 250 MPa was applied to the specimen in a chamber contained hydrogen atmosphere (580 kPa) at room temperature. After the test, topologies of the fracture surface and the side surface of the specimen were observed by field emission scanning electron microscopy (FE-SEM). Dislocation structure and plastic strain distribution beneath the fracture surface were investigated by electron channeling contrast imaging (ECCI) and electron backscattering diffraction (EBSD), respectively. The crack propagation was discontinuously and left striation pattern on the fracture surface. Extensive plastic deformation was observed to accompany crack propagation. The crack tip plastic deformation associated with hydrogen effect during the crack propagation leaves three adjacent regions beneath the fracture surface: (Region A) the region immediately beneath the fracture surface has an extremely high plastic strain, (Region B) the region adjacent to Region A has high dislocation density and high plastic strain, and its width is constant despite crack length increases, (Region C) the region away from the fracture surface has low dislocation density and low plastic strain, and its width linearly increases with crack length. These findings reveal the effects of plastic deformation and hydrogen-dislocations interaction around the crack tip on the rate-limiting process of hydrogen-induced delayed crack propagation in thin specimens.

10:00 **High-Cycle Fatigue Behavior of Single Crystalline Ni-Mn-Ga Magnetic Shape Memory Alloys**

J. Heider (Sp)[1]; E. Pagounis[1]; M. Laufenberg[1]
[1]ETO MAGNETIC GmbH, Stockach (Germany)

Magnetic Shape Memory (MSM) alloys are a class of smart materials exhibiting the ability to change size and shape when subjected to a magnetic field or an external stress, generating, thus, force and motion [1,2]. The effect is based on the reorientation of twin variants in the martensitic phase [3]. MSM alloys are promising candidates for application in actuators, sensors, dampers, and energy harvesting devices due to their outstanding properties. These applications demand materials with minimal fatigue effects during millions of actuation cycles.
The present study focuses on the changes in microstructure of single crystalline off-stoichiometric Ni2MnGa samples exhibiting a five-layered (10M) superstructure and up to 7% strain during high-cycle actuation in a custom-built testing device.
The magneto-mechanical properties indicate a decrease of strain, twinning stress, and work output density during actuation cycling of up to 100 million times. The development of cracks corresponding roughly to the {111} crystal planes is found to be associated, among others, with the presence of impurities or inclusions in the material. Crack growth occurs mostly along the low angle boundaries with varying tilt. The twinning microstructure after fatigue can be characterized by pinned twin variants and branching behavior of twins due to the formation of persistent slip bands containing both edge and screw dislocations pinning the mobile twin boundaries. The fracture plane is perpendicular to the {101} twin planes and follows the ladder structure of the persistent slip bands comprised of edge dislocations. Steps in the fracture plane correspond to changes in the modulation direction.

10:20 **Roles of defects in high cycle fatigue of a powder nickel base superalloy**

L. Ying (Sp)[1]
[1]Beijing Institute of Aeronautical Materials (China)

The high cycle fatigue behavior of a powder nickel base superalloy under different temperature and stress was studied. The results show that the internal defects in the Powder Superalloy play an important role in the process of high cycle fatigue. At room temperature, the fracture fatigue cracks all start from the surface of the sample, most of the fractures are point-shaped, single source characteristics, individual fractures have multiple fatigue sources, and each fatigue source is point source; the source area is small plane like cleavage characteristics; at high temperature, the fracture fatigue cracks all start from the inside of the sample, at the same temperature, the fractures under low stress conditions are mostly from internal defects The defects are all oxide inclusions of Al and Mg. Under the condition of high stress, the cracks all originate from the internal point, and there are no defects in the source area, which are characterized by small cleavage like plane.

11:10 **Effect of applied stress amplitudes on the growth behavior of fatigue cracks in ultrafine grained Cu specimen with a small-hole**

M. Goto (Sp)[1]; T. Yamamoto[1]; S. Han[2]; J. Kitamura[1]
[1]Oita University (Japan); [2]Korea Institute of Materials Science, Changwon (South Korea)

Using ultrafine-grained copper processed by equal channel angular pressing, the growth mechanism of surface-cracks at high- and low-cycle fatigue regimes was studied by the constant and two-step stress amplitude tests. The crack growth direction depended on the location along the circumferential direction of the round bar specimen and on the applied stress amplitudes. A small blind hole as a crack starter was drilled on the surface where an intersection between the shear plane of the final pressing and the specimen surface makes an angle of 45° with respect to the loading axis. The crack from the hole grew with a 45° inclination to the loading axis at stress amplitudes above 180 MPa. At the stress amplitude less than 160 MPa, however, the crack grew perpendicular to the loading axis. The physical background of deferent crack path directions between high- and low-stresses was discussed in terms of the microstructural evolution caused by cyclic stressing and the morphological feature of surface damage around the crack paths.

11:30 **Detection and prediction of high temperature fatigue crack growth around notches in polycrystalline Nickel base alloy**

A. Butz (Sp)[1]; B. Fedelich[1]; B. Rehmer[1]; S. Schmitz[2]
[1]Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin (Germany);
[2]Siemens AG, Berlin (Germany)

Film cooling is a common way to reduce the surface temperature of turbine blades. The cooling air is pumped through multiple small holes through the structure. A drawback is that cracks readily initiate at these holes. Conventional fatigue models cannot be applied to the holes in a straightforward manner. Indeed, the high stress gradients reduce the crack growth rates in comparison to smooth specimens. In addition, a statistical effect appears due to the small size of the highly loaded surface. Nickel base superalloys used for blade material have large grain sizes (>1 mm) and the nucleated short cracks mainly grow in a single grain, which increase the scatter. Finally, the surface state of the laser drilled holes significantly differ from that of laboratory smooth specimens due to partial melting of the alloy.
As part of an ongoing project, our group carries out high temperature LCF (Low-Cycle-Fatigue) tests with center hole specimens of a coarse-grained Nickel base Superalloy. Here, not only the large grain size, but also the shape of the starting crack around the notch is assumed to be of high importance for fatigue life and thus, needs to be considered in a fatigue life prediction model. A new combined procedure to detect the shape of the starting crack using the potential drop method and induction thermography will be presented. Moreover, LCF lifetimes of specimen with differing surface finishes in the hole were compared and the results were used for the identification of a fracture mechanics based model for the prediction of fatigue life time.





11:50 **Defect-induced fatigue mechanism and microstructure-based life prediction approach of nickel-based superalloy at elevated temperature**

W. Li (Sp)[1]; X. Li[1]
[1]Beijing Institute of Technology (China)

Fatigue of structures or materials from repeated loading in all fields of engineering covers an enormous variety of topics, in which the very-high-cycle-fatigue (VHCF) associated with micro-scale defects or cracks induced failure is becoming the focus of attention in recent years. In this paper, the fatigue properties of a nickel-based superalloy under symmetrical and asymmetrical loads were experimentally examined at elevated temperatures in the high-cycle-fatigue (HCF) and VHCF regimes. By using the scanning electron microscope, energy dispersive X-ray spectrometer and three-dimensional imaging analysis, the micro-scale crack morphologies on the fracture surfaces were observed, and the emphasis was on studying the surface and subsurface crack nucleation and early growth behavior. Combined with the analysis of stress-life characteristics, the discussion of characteristic crack size and the evaluation of stress intensity factor at the crack tip, the failure mechanisms of nickel-based superalloy at elevated temperatures in the HCF and VHCF regimes were elucidated. Through the definition of transition crack sizes and the microstructure-scale parameters such as grain size, dislocation number, slip band width, etc., a theoretically modeling approach was proposed to predict the fatigue life of nickel-based superalloy associated with failure mechanism at elevated temperatures in the HCF and VHCF regimes.

12:10 **Bending fatigue of high strength strip steel at 20 kHz and the influence of defects**

M. Tofique (Sp)[1]; J. Bergström[2]; M. Sadek[2]; A. Löf[1]; C. Millward[1]
[1]voestalpine Precision Strip AB, Munkfors (Sweden); [2]Karlstad University (Sweden)

High strength strip steel is used in many applications as in engines and compressors. High precision in dimensional tolerances, good surface finish, high tensile strength and fatigue strength are required. One vital requirement is a high fatigue strength at long life lengths, and, hence, it is related to high cleanness of the steel microstructure with minimal internal or surface defects. One application is the use in flapper valves where high fatigue strength in combination with impact fatigue strength is demanded. A high static strength and adequate damping of valve material are also desired. One concern in characterization of the material is difficulties in obtaining the fatigue strength of the thin high strength strips, and in particular the bending fatigue strength. The present study has its focus on the development of a method to obtain the bending fatigue strength at 20 kHz fatigue load frequency, and to evaluate the influence of defect distribution on the fatigue strength. An ultrasonic 20 kHz test instrument working in resonance along the load train is used, and with a bending fixture and a specimen geometry particularly developed for this purpose. Reference testing in uniaxial fatigue of strip specimens is performed. Evaluation of initiating defect distributions and crack initiation mechanisms as fine granular area (FGA) assessments are made by SEM fractography. LOM and SEM-EBSD microstructure and mechanical characterization are performed. Final analysis of the fatigue strength and its dependence on defect distributions is performed using failure probability statistics.

16:40 **Effects of surface and material imperfections on the durability and structural integrity of bearing components**

J. Lai (Sp)[1]; H. Huang[1]
[1]SKF, Houten (Netherlands)

Bearings are critical machine components for mechanical power transmission. The challenge of ever increasing power density from modern equipment manufacturing imposes a higher demand for the load-carrying capacity on one hand and reliability of bearings on the other hand. Catastrophic failure such as fracture of bearing components in applications must be avoided.
High-strength materials such as hardened bearing steels, can suffer in general from lack of damage tolerance in the form of sensitivity to pre-existing imperfection features. The detrimental effects of the imperfection features must be properly accounted for in the design and structural integrity evaluation of engineering components. The present study focuses on a specific type of imperfection feature, i.e. surface roughness resulting from machining, which is relevant for bearing flanges and flanged parts of bearing units.
Rotating bending fatigue (RBF) tests were conducted on a high-carbon steel in martensitic and bainitic conditions, and a tough-tempered medium-carbon steel. The specimens were surface-finished to different conditions: polished surface and ground surface with a range of roughness levels. The experimental results indicate that the hardened high-carbon steel specimens with rough surface failed predominantly by surface crack initiation, whereas the fatigue fracture of the specimens with smoother surface tend to fail by subsurface crack initiation from non-metallic inclusions. Moreover, the fatigue strength of the martensitic specimen is lower than that of the bainitic specimen in the low stress-cycle range in which failure is dominated by surface initiated fatigue fracture, whereas this difference diminishes in the high-cycle fatigue regime where subsurface initiated fatigue prevails. The non-hardened medium-carbon steel samples, however, fail only by surface crack initiation, and the fatigue strength is much less sensitive to surface roughness.
A unified model is developed to predict the fatigue strength of structural components with different microstructures and surface finish. The model is used to predict the fatigue strengths of flanged bearing rings subjected to thrust loading. A fairly good agreement is achieved between the model prediction and experiments

17:00 **A Method for Generating Periodic Statistically Equivalent RVEs Incorporating a Periodic Mesh and Inclusions Generated by a Machine Learn Algorithm.**

M. Henrich (Sp)[1]; S. Münstermann[1]
[1]RWTH Aachen University (Germany)

The use of Advanced High Strength Steels (AHSS) is very popular in the automotive industry. Within this industry the scope for these materials is widely spread. Therefore, the mechanical properties have to satisfy a variety of requirements. In order to fulfill the desired requirements of modern technology, AHSS are tailored for different mechanical properties such as formability or crash strength. The process of tailoring these materials leads to multi-phase microstructures, with increasingly complex morphologies. To capture the influence of these morphologies on the mechanical properties it is a common method to simulate Representative Volume Elements (RVEs). RVEs are generated on the basis of statistical data and algorithms using randomization methods. This study introduces an RVE Generator with the ability to generate statistically equivalent and periodic RVEs. In addition, the RVEs are periodically meshed so that periodic loading conditions can be applied. For further investigations of the microstructure it is also possible to model realistic inclusions inside the RVEs. These inclusions are based on a Machine Learn Algorithm (MLA) which was trained with pictures of sliced Inclusions within a steel matrix.



28 May 2020 FDMD 2020

Session **Steel**

09:40 **Active crack obstruction in high performance ferritic (hiperfer) steels**

T. Fischer (Sp)[1]; B. Kuhn[1]
[1]Forschungszentrum Jülich GmbH (Germany)

Future thermal energy conversion systems (e.g. concentrating solar power, energy thermal storage power plants etc.) will be characterized by highly dynamic changes in operating conditions. Therefore, in contrast to advanced ferritic-martensitic (AFM) steels, which were primarily developed for high creep rupture strength, the materials used in such plants must have increased fatigue resistance.
The stainless High performance Ferritic (HiperFer) steels, developed at Forschungszentrum Jülich, Germany, combine excellent creep rupture strength and increased resistance to steam oxidation up to temperatures of 650 °C and beyond. The relevance of creep strength nevertheless remained high in development, because it results in low component wall thickness and thus helps diminishing thermal stresses during operation. Furthermore a unique concept for fatigue strengthening was implemented in these steels to withstand increased thermomechanical fatigue loading of flexible power plant operation. The crack initiation (thermomechanical fatigue) is actively obstructed by thermomechanically induced particle precipitation; the crack propagation (fatigue crack growth) is additionally obstructed by subgrain formation and resulting crack deflection. A further advantage of HiperFer steels is its grain structure being stable even under severe cyclic loading, while highly energetic martensitic lath structures of AFM steels is instable and suffers polygonisation. In comparison to grade 92, the residual life time of HiperFer is up to a factor of 10 longer. Further development of HiperFer aims at increased particle density and optimized heat treatment to reach more effective retardation of crack nucleation and lower crack propagation rate and thus a further increase of cyclic operation life time.

10:00 **Influence of filters with functional coatings on non-metallic inclusions in 42CrMo4 steel and resulting mechanical properties**

M. Seleznev (Sp)[1]; S. Henschel[1]; E. Storti[1]; C.G. Aneziris[1]; L. Krüger[1]; A. Weidner[1]; H. Biermann[1]
[1]Technische Universität Bergakademie Freiberg (Germany)

Reduction of the non-metallic inclusions (NMI) content is crucial for obtaining high quality steel and other alloys. This is achievable by different refining methods, among which metal melt filtration by ceramic foam filters is a very promising one. Steel refining by ceramic foam filters can be divided into two principal mechanisms: active and reactive filtration. To study the influence of different reactive filter coatings on NMI population and mechanical properties of 42CrMo4 steel prismatic (125×20×20 mm3) ceramic foam filters based on carbon-bonded alumina were produced by the replica technique. Functional coatings were applied on the filters by cold spray coating and the filters were heat treated again under reducing atmosphere. Several types of filter coatings were investigated: reference filter with no coating; alumina (Al2O3); alumina-based slurry (AC5); carbon nano-tubes (CNT) with alumina nano-sheets (ANS); and calcium hexaluminate (CA6).
Filters were immersed in a 42CrMo4 steel melt within a specially designed steel casting simulator. The solidified steel was analyzed with respect to the size distribution and the chemical composition of the remaining non-metallic inclusions (NMI) by means of sections imaging, chemical extraction and fractography. Cyclic loading and quasi-static tests were performed in order to determine the fatigue limit, the strength, deformability and toughness of the steel after filter immersion. The main results can be summarized as follows:

1) The application of the CA6-coated filter led to the most significant changes in NMI population in comparison to the reference state by reducing the total number of NMIs to 70%.
2) The chemical analysis of NMIs revealed mostly pure alumina and other oxides (e.g. CaO, SiO2, and mullite (Al2O3-SiO2)). All tested filter coatings reduced the total amount of alumina and increased the total amount of other oxides.
3) Plate-like alumina inclusions were the most detrimental in terms of fatigue strength causing 100% of fatigue cracks. Treatment with the CA6-coated filter resulted in the lowest fatigue limit due to the largest NMIs and in the same time in higher deformability and energy dissipation due to the lowest total NMIs density.

The implementation of an active + reactive filter system for two-stage steel cleaning is believed to be an effective method for removal of both small and large NMIs from the steel.

10:20 **Fatigue Cracked Helicopter Gears that Initiated from Exogenous Inclusions and Subsequent Fatigue Testing to Evaluate Micro-Cleanliness of the VIMVAR Steel**

A. Slager (Sp)[1]
[1]Bell Helicopter, Fort Worth (United States)

Examples of several fatigue cracked helicopter gearbox gears made from VIMVAR steel that initiated at exogenous inclusions will be presented. One inclusion cluster that measured 0.46 mm by 0.13 mm was traced back to the VIM crucible refractory brick. Shot peened axial fatigue test specimens were used to evaluate inclusion type, size, and prevalence for various steel mills for this particular steel alloy. As expected, scatter in the data was observed due to the limited number of specimens and the inclusion size/type, but some trends did emerge.



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11:10 **Enhancement of the damage tolerance as an answer to increasing requirements in high strength steels**

B. Clausen (Sp)[1]; H.W. Zoch[1]
[1]Leibniz Institute for Materials Engineering - IWT, Bremen (Germany)

The requirements towards high strength steels in engineering applications are continuously increasing. These requirements do not only address the maximum fatigue strength in itself, but also the scattering of local properties is of increasing importance. Since at the same time the acceptance of failures in industry is decreasing, following the „zero defect strategy", the reduction of scattering in fatigue life supersedes the importance of its average value. An approach to meet these requirements is the development of microstructures which are more damage tolerant.
At Leibniz IWT this general approach has already a certain tradition. In the presentation three different approaches for through- and case hardening bearing steels, investigated in the context of current research projects, are compared. The first is based on the generation of fine bainitic microstructure in standard bearing alloys, which allows higher plastic deformation at significant strength levels. The second is the development of high strength steel grades with alloying elements stabilizing retained austenite within the heat treatment procedure. As third variant case hardening steels were carbonitrided to stabilize the retained austenite due to the enhanced nitrogen content in the case. The reason for enhancement of the damage tolerance due to an elevated and stabilized retained austenite content is assumed in the locally enhanced plasticity and its possible stress induced transformation into martensite. The effect achieved by the different approaches will be discussed and guided to an outlook.

11:30 **Ultrasonic fatigue of AISI 4140 at elevated temperatures**

A. Schmiedel (Sp)[1]; H. Biermann[1]; A. Weidner[1]
[1]Technische Universität Bergakademie Freiberg (Germany)

In this study, the fatigue life of cast steel AISI 4140 in two different heat treatment states was investigated at room temperature, 473 K and 773 K in the range of VHCF up to 10^9 cycles. The detrimental effect of the cast defects on the fatigue strength and the influence of temperature as well as hardness of the steel matrix determine the fatigue life. Fracture surfaces were analysed regarding crack initiating defects and discussed with fatigue life data. The SN-curves obtained at room temperature and at 473 K show a large scatter. However, the SN-curve at 773 K exhibits a larger slope and a surprisingly small scatter. Thus, fatigue lives of the specimens tested at 773 K were described on basis of a crack growth model. It is shown, that the fatigue behaviour of the cast steel AISI 4140 changes from 473 K to 773 K and no fatigue limit was observed at high temperature in the range of VHCF.

11:50 **Influence of laser welding defects on the high cycle fatigue behavior of stainless duplex steel 1.446[2]**

A. Odermatt (Sp)[1]; L. Pan[1]; V. Ventzke[1]; N. Kashaev[1]
[1]Helmholtz-Zentrum Geesthacht (Germany)

A good corrosion resistance in combination with a relatively high strength make the nitrogen alloyed duplex steel 1.4462 (X2CrNiMoN22-5-3) favorable for the applications in chemical industry, paper and cellulose production, food industry and sea water piping. The stainless steel is therefore a very good choice for structural applications, where innovative joining processes such as laser beam welding are required. In case of 1.4462 steel welds show higher strength in comparison to that of the base material. In spite of usually acceptable static strength level, fatigue and damage tolerance characteristics of the laser beam welded 1.4462 joints are relatively poor due to inherent welding-induced defects, which are inevitable results of the laser beam welding process. The detrimental effect of defects is further enhanced by the formation of hard and notch-sensitive dendritic two-phase microstructure within the welding seam. In the current work, the quality of laser beam welded joints was characterized in terms of weld morphology, microstructure and mechanical properties. A particular emphasis of the present study is placed on investigating the effect of various welding defects on the high-cycle-fatigue performance of laser beam welded joints. Furthermore, a model to predict the fatigue properties in the high cycle fatigue regime is proposed. The fatigue-life assessment model has been developed for internally flawed materials based on the fracture-mechanics approach, which takes into account the short-crack effect.

12:10 **Increasing the Very High Cycle Fatigue Strength of High-Strength Steels (100Cr6 and 42CrMo4) by Thermomechanical Treatments**

J. Sippel (Sp)[1]; A. Khayatzadeh[2]; S. Guth[2]; K.-H. Lang[2]; E. Kerscher[1]
[1]TU Kaiserslautern (Germany); [2]Karlsruhe Institute of Technology (KIT) (Germany)

Under very high cycle fatigue (VHCF) loading, failure of high-strength steels is mostly initiated at internal imperfections, such as non-metallic inclusions. This is in contrast to classical low cycle fatigue (LCF) and high cycle fatigue (HCF), where cracks initiate mostly at the surface. Furthermore, there is a specific crack initiation mechanism observed in VHCF, whereby a so-called fine granular area (FGA) is formed in the immediate vicinity of the crack-initiating non-metallic inclusion. This FGA consists of a very fine-grained microstructure, which is produced by the localization of the cyclic stresses and thus a localized plastic deformation around the inclusions. The local grain refining is probably due to the formation of energetically favourable dislocation cells in the plastic zone around inclusions. Those cells build new grain boundaries during further cyclic loading and these smaller grains cause a reduced threshold value of the stress intensity factor for long crack growth leading to failure at lower stress amplitudes in VHCF than in HCF.
The aim of our project is to increase the VHCF-lifetime and the VHCF-strength. Therefore, it is our hypothesis that it is necessary to suppress the above mentioned grain refinement process by a stabilized dislocation structure. This stabilized dislocation structure might be realized by a thermomechanical treatment (TMT) process applied in the temperature range of maximum dynamic strain aging. During the TMT, particularly in the area of stress exaggeration, in the immediate vicinity of the non-metallic inclusions, the dislocation structures are modified, stabilized and, thereby, counteract grain refinement during VHCF loading.

In order to verify the effect of dynamic strain aging on the VHCF-fatigue strength ultrasonic tests were carried out up to the ultimate number of 109 cycles. Additionally, fracture surfaces and microstructure were investigated for thermomechanically treated and untreated specimens.





14:10 **Increasing the High Cycle Fatigue Strength of High-Strength Steels (100Cr6 and 42CrMo4) by Thermomechanical Treatments**

A. Khayatzadeh (Sp)[1]; J. Sippel[2]; S. Guth[1]; E. Kerscher[2]; K.-H. Lang[1]
[1]Karlsruhe Institute of Technology (KIT) (Germany); [2]TU Kaiserslautern (Germany)

The fatigue limit of high strength steels is one of the most important mechanical properties for applications. With a suitable thermo-mechanical treatment (TMT) in the temperature range of maximal dynamic strain aging (DSA) the high cycle fatigue (HCF) limit may be increased.
During a TMT in the DSA temperature range dislocations interact with alloying element atoms (e. g. carbon in case of steels) and are impeded in their movement. Finally, a stabilised microstructure with increased dislocation density is formed which may exhibit a higher HCF strength.
In this study the effect of TMT on the fatigue limit of quenched and tempered steels 100Cr6 (AISI 52100) and 42CrMo4 (AISI 4140) has been investigated. In a first step, the temperature where the maximal DSA occurs has been determined searching a maximum of hardening under cyclic loading. At this temperature, the material was subjected to 50 cycles of sinusoidal loading with increasing stress levels to strengthen the microstructure (TMT). Subsequently, stress-controlled push-pull fatigue tests were conducted in the HCF-regime on solid round specimens with and without TMT as well as with polished and non-polished surface.
It was found that for non-polished specimens the effect of TMT on the fatigue strength is insignificant. For polished specimens the TMT enhances the fatigue life significantly. The fatigue strength of polished specimens without TMT is comparable to that of non-polished specimens. Thus, the positive effect of TMT on fatigue strength depends on the surface quality. To investigate the acting damage mechanisms specimen and fracture surfaces were analysed using SEM.

14:30 **Influence of forging defects on fatigue behaviour of a rotor steel**

A. Aydin (Sp)[1]; I. Varfolomeev[1]; C. Amann[2]; K. Kadau[3]
[1]Fraunhofer Institute for Mechanics of Materials IWM, Freiburg im Breisgau (Germany);
[2]Siemens AG, Mülheim a. d. R. (Germany); [3]Siemens Energy Inc., Charlotte, NC (United States)

Structural components produced by casting and forging may contain internal defects detected by means of ultrasonic testing (UT). The decision whether such a component can be taken into operation or should be withdrawn depends on the defects size, applied load and material properties. Currently, the fracture mechanics methodology is widely used to estimate the severity of UT indications, while assuming a sharp initial crack which contour envelops the respective indication. However, such an approach may considerably underestimate the remaining fatigue life of the component, since neither the defect morphology nor the phase of crack nucleation from an individual defect or a defect field are taken into account.

In this study, a series of fatigue tests were performed to quantify the effect of manufacturing defects on the fatigue life of a rotor steel. First, material S-N curves were derived in stress controlled HCF and strain controlled LCF tests, using small cylindrical specimens with no defects. Further tests on the defect-free material were carried out using larger cylindrical specimens with a diameter Ø25 mm. Finally, large cylindrical tension specimens with embedded defects located close to the centre as well as four-point bend rectangular specimens containing sub-surface defects were tested. In all cases, the defect position in the specimen was estimated based on UT measurements on material segments extracted from a rotor disc. After testing, fracture surfaces were examined by SEM to determine the type, size and location of the defect at which crack initiation occurred, as well as to estimate the number of cycles until crack initiation by means of beach-marks produced on the fracture surfaces during the test.

The experimental results were analysed to correlate the defect type and size with the fatigue life, on the one hand. On the other hand, different fatigue assessment approaches were applied to predict fatigue lives of individual specimens based on the respective UT indications and quantitative information derived from fractographic investigations. When doing this, finite-element models were established representing different defect configurations, while varying the size and number of defects in the model. Results of finite-element calculations of the stress and strain fields for different defect configurations and their correlation to the experimentally obtained fatigue lives are discussed in the paper.

14:50 **Corrosion fatigue damage mechanisms of a new high strength steel for aeronautical applications**

C. Rousseau (Sp)[1]; M. El May[1]; N. Saintier[1]; A. Oudriss[2]; X. Feaugas[2]
[1]Arts et Métiers, Talence (France); [2]La Rochelle Université (France)

To meet the highest performance and reduce the emissions, a new martensitic age-hardening steel has been developed for aircraft engines structural parts. Its very high mechanical resistance guarantees the reliability of structures over long services life. However, airplanes may operate in environments likely to cause pitting corrosion and impact their fatigue performance. Indeed, pure tensile cyclic loading tests conducted in 5 g/L NaCl solution have shown a significant reduction of fatigue strength compared to dry air. Similar results are found for high strength steel, mainly attributed to corrosion defects as preferred sites for crack initiation, crack growth assisted by electrochemical dissolution or hydrogen embrittlement [1–3]. Concerning the material under study, detailed post-mortem sample observations allow to draw the following conclusions. First, localized corrosion is enhanced by cyclic loading. The higher the maximum applied stress, the more pits on surface at failure. Then, fatigue cracks are initiated on critical size pits. The early stage of crack growth is strongly reliant on corrosion. Both material dissolution and applied stresses contribute to propagation by a competitive process. As the crack is growing, the impact of dissolution is decreasing. Finally, growth rate becomes mainly controlled by applied stresses. However, the role of hydrogen introduced during corrosion processes is still questioned. Considering the above, the total corrosion fatigue lifetime can be divided into three contributions: the number of cycles to initiate one or several cracks from corrosion pits with a critical size, the number of cycles for "pit-to-crack" transition, and the number of cycles for crack growth until failure. Based on existing modelling approach for each contribution [4], a comprehensive model is proposed. A reasonable agreement is found between empirical and predicted lifetimes.

15:10 **Effect of Welding Procedure on the Fatigue Resistance of High-Strength Steel Butt-Welded joints**

N. Gubeljak (Sp)[1]; C. Steimberger[2]; N. Enzinger[3]; W. Ernst[4]; M. Chapetti[5]
[1]University of Maribor (Slovenia); [2]National University of Comahue, Neuquén, (Argentina);
[3]Graz University of Tehnology (Austria); [4]Voestalpine Stahl GmbH, Linz (Austria);
[5]Research Institute for Material Science and Technology (INTEMA), CONICET - National University of Mar del Plata, Mar del Plata, Argentina (Argentina)

Experimental and analytical analyses were carried out in order to assess fatigue behaviour of high-strength steel butt-welded joints. Samples were manufactured with steel S960MC and S960QT and different welding techniques: Gas Metal Arc Welding (GMAW), Laser Hybrid Welding (LHW) and Electron Beam Welding (EBW). Fatigue tests were performed under the four points bending scheme, with stress ratio R = 0.1. All specimens showed fatigue crack initiation and subsequent growth from the weld toe area, near the heat affected zone (HAZ), although different S-N curves were obtained for the different welding procedures. Residual stresses, microstructure, hardness and joint geometry resulting from each technique were analysed and their effect on the fatigue resistance of the welds was evaluated by means of an integrated fracture mechanics methodology. This approach was applied to estimate the relative influence of the different geometrical and mechanical parameters of the weld. Joint geometry was found to be the most influencing factor.





Session **Postersession**

P03 **Impact of mechanical operating damages on the fatigue life of the aircraft compressor blades**

A. Bednarz (Sp)[1]
[1]Rzeszow University of Technology, Rzeszów (Poland)

Presented research work shows fatigue analyzes for three different types of notch observed on the leading edge of the aircraft engine compressor blade. The main goal of this research was to create information about the impact of different parameters of the notch (like location, depth, nature of formation) affect on the number of the load cycles to various sizes of the fatigue gap. The topic of crack initiation and the very development of the fatigue crack was discussed. The work presents the results of fatigue tests in resonance conditions. The I-st stage compressor blade was examed in the first mode of resonance (flexural bending) with a constant amplitude of the blade tip (1.8 mm). The impact of the notch type on the crack initiation process and on fatigue durability was discussed. Obtained results show the influence of plastic deformation on element life. The quantitative influence of the nature of the notch formation on the crack propagation process at its initial stage was determined. The relationship between damage caused during engine operation and damage made for the purposes of the experiment is shown. The influence of initial stresses resulting from the plasticization of the material around the notch tip on the initiation of a fatigue crack is presented.

P07 **Analytical solution for stresses and deformations in and near an elastic spherical inclusion in an infinite elastic solid**

M. Vormwald (Sp)[1]; H. Amstutz[1]
[1]Technische Universität Darmstadt (Germany)

In the present work, solutions are recapitulated according to the theory of elasticity for the deformations of spherical inclusion in an infinite matrix under remote uniform axial and axial-symmetrical radial tension. Stress fields in the inclusion and at the interface in the matrix are provided, too. It is shown that the sphere is deformed to a spheroid under any of the loading cases considered. Due to the axial-symmetric setup of the problem, the deformation is fully described by the two displacement values at line segments on the principal axes of the spheroid. The displacements depend on the applied remote load and on two traction fields at the inclusion-matrix interface. For any combination of inclusion and matrix stiffness, the condition of compatibility of deformations yields a system of two linear equations with the two magnitudes of the tractions as unknowns. Thus, the problem is reduced to a formulation for solving a two-fold statically indetermined structure. The approach follows a procedure outlined in detail in reference [1] for solving a different problem of the Theory of Elasticity.

The system is solved and the exact solution of the general spherical inclusion problem with differing stiffness in terms of Young's moduli and Poisson's ratios of inclusion and matrix is presented.

[1] Hans Amstutz, Michael Vormwald: Analysis of an elastic elliptical inclusion in an infinite elastic plate under uniform remote tension based on the solution of the corresponding cavity problem. J. of Strain Analysis for Engineering Design 52(8) 515-527, 2017

P70 **Analysis of Ballistic Impacts on Composite materials by Infrared Active Thermography**

S. Boubanga Tombet (Sp)[1]; E. Guyot[2]
[1]TELOPS, Morangis (France); [2]Telops, Paris (France)

Since the beginning of the last century the ongoing advances in materials engineering have led to an unrestrained development of new technologies. Composite materials are the ones attracting most attention because they have many advantages over their homogeneous counterparts. These include high specific stiffness and high specific strength combined with a significant reduction in weight making them attractive for many industrial applications. One of the most important fields of application is the defense industry were the composites properties such as low weight, rigidity, strength and durability are of key importance. Composite materials made from artificially obtained high strength fibers are particularly interesting. These composites are characterized by many fiber-reinforced properties that make them ideal for ballistic protection applications. The ballistic protection equipment should protect the user from for instance arms fire. The proper analysis strategy of the area of internal damage caused by the impact of bullets is very important in the research and evaluation of protective composite ballistic equipment. Damage to the internal structure of the composite coating material can only be assessed using non-destructive testing methods. This work focused on the assessment of the damaged area on composites ballistic plates subjected to high velocity impact. Active pulsed thermography technique was used for performing post-mortem analysis of the impacted specimens. The post-mortem analysis was combined with inputs of the velocity of the projectile, the absorbed energy to evaluate how efficient the material is at spreading the absorbed energy to a large area. M16 rifle using 5.56 mm caliber bullets was used to fire shots threw a wooden laminate located at a distance of 10 m in front of the firearm. High speed visible cameras were used to measure the projectile velocity before and after the sample, Telops high-speed IR camera was also used. Active thermography experiments were conducted with Telops new NDT solutions called TESTD. Flash lamp source with pulse energy of 6 KJ was used to excite the sample after the ballistic testing. Telops high definition IR camera was used to capture the sample cooling after the pulse heating and Fourier transform analysis were conducted to obtained phase images.

P86 **Effects of heat treatments on 2017A fatigue behavior**

A. May (Sp)[1]
[1]Ecole Militaire Polytechnique, Algier (Algeria)

The present work is dedicated to the study of the effect of heat treatments on the cyclic behavior of a 2017A aluminum alloy, which is widely used in the aerospace industry. We are interested in the evolution of fatigue behavior, the first loading cycles as well as the total life until fracture, for several states of heat treatment. The samples have already been passed to the homogenization heat treatment in order to erase all the unknown history of the studied alloy. Then, a structural hardening is applied by making two groups of samples, one quenching with iced water and the other quenched with liquid nitrogen. For both groups, we performed several series of maturation at different temperature levels. The treated samples were subjected to cyclic strain-controlled loading. Other characterization tests were performed such as hardness tests and microstructural analyzes using the Scanning Electron Microscope. The results of these investigations explain why the different lifetimes obtained for the samples tested.





P97 **Optimize Performance and Efficiency of 3D Paper Printing**

D. Abdullah Agha (Sp)[1]; U. Knaack[1]
[1]Technische Universität Darmstadt (Germany)

The research investigates the controlling of the printing quality and the printing defects through the process of the production of paper 3D printed-objects from semi-liquid paste as inputted materials of the cellulose and it's derivative with other components and water using additive manufacturing technology by using the machine (LUTUM® 3D clay PRINTER) and taking into consideration the typical printing properties that affect haptic printing results.
Cellulose is the world's most abundant biopolymer and is inherently a low cost and widely available material. Moreover, it is environmentally friendly and easy of recycling and required low energy consumption in manufacturing because of ease of dissolve into water. So the question is how we can be able to produce an object from this cheap material with perfectly desired accuracy and structure integration? That is depending on the raw materials, the mix design, and the process of manufacturing. One of these effects that maniple and dominated the geometrical accuracy of the 3D printed objects in comparing with the wanted geometrical result is the printing characteristics like the printing settings, filament settings, and the printer settings. When performing an object printing with selecting the suitable nozzle diameter, where there are several nozzles and with each nozzle has selective values for the printing characteristics to control the capacities and extruder settings and that will eliminate the defect of not straight lines "Zick zack" of the infill lines in the printed results and give a right compatible balance for the speeds and flow rates to extrude.

P116 **Defect-based assessment of ‚as-built' surfaces for Ti6Al6V produced by SLM**

L. Barricelli (Sp)[1]; S. Beretta[1]; L. Patriarca[2]; M. Riccio[2]
[1]Politecnico di Milano (Italy); [2]Beamit, Fornovo (Italy)

Design of load-carrying components obtained by additive manufacturing subjected to cyclic load is widely investigated. Factors such as surface quality, microstructural defects, printing orientation, residual stress, heat treatment, geometry and size are the main variables involved in the fatigue assessment of these components. A deeper understanding of the aforementioned variables effects is necessary and it has been mainly investigated by experimental studies. This study investigated the effects of of the ‚as-built' condition on the fatigue properties of an Ti6Al4V alloy manufactured by SLM in different orientations and annealed. The bending fatigue results and surface quality assessment did not evidence a strong correlation with roughness parameters. On the other hand, an analysis based on the size of the features at the fracture origin proved to be successfull as a surface rating. Analyses including the ‚short crack effect' [1] allowed us to estimate Equivalent Initial Flaw Size (EIFS) close to the real critical features [2, 3]. The EIFS allowed to fairly predict the life of specimens tested in the different orientations.

P120 **Effect of notch on fatigue behavior of 7175 aluminum alloy**

M. Kalienko (Sp)[1]; M. Leder[1]; A. Gugel[1]; A. Volkov[1]
[1]PSC VSMPO-AVISMA, Verkhnaya Salda (Russia)

High strength age hardenable aluminum 7XXX series alloys based on the Al–Zn–Mg–Cu system are widely used in the aircraft and automotive industries for structural components because of its exceptionally high strength to weight ratio. Fatigue life of a component depends strongly on its surface condition. Fatigue cracks are generally considered to nucleate at the surface and therefore surface topography plays an important role in determining the fatigue life. It was established that surface roughness is supposed to introduce stress concentrators that encourage the crack nucleation and accelerates the early fatigue crack growth, hence reducing fatigue life compared to perfectly smooth specimens. The present research reports comparative analysis of notch effects on fatigue behavior of aluminum alloy 7175-T7451. The axial fatigue testing was performed at ambient conditions on smooth specimens and with notch on the surface in form of etch pits. Experimental results revealed reduction in fatigue life of specimen with notch due to decrease the nucleation time of crack initiation. Scanning electron microscopy technique was used to observe fracture and estimated step of fatigue crack grow.

P121 **Structure-Property relationship of aerospace grade Aluminium-7075 under Monotonic and Fatigue loading**

G. Kumar (Sp)[1]; H. Maharaja[1]; A. Gokhale[1]; S. Mishra[1]
[1]Indian Institute of Technology Bombay, Mumbai (India)

Understanding of fatigue and fracture behaviour of Aluminium alloys is of prime importance when it comes to aerospace applications. The 7xxx series of this alloys, owing to its high strength, find extensive application in the aerospace industry. The main alloying elements in 7xxx alloys are Zinc,-Copper and Magnesium. These elements are available in the form of precipitates and provides high strength when alloy is age hardened. Al-7075 is the most widely used alloy in aircraft in the 7xxx series. Aerospace structures like upper wing surface , fuselage etc. are often subjected to fatigue loading. A very detailed analysis has been carried out which includes uniaxial fatigue test (room temperature) , fatigue crack growth analysis , K1C and J1C(mode 1 fracture analysis). Tensile and compression tests have also been conducted to find out the mechanical properties of the aluminium alloy. In addition to this, Hardness tests have been performed before and after the tensile tests to measure the effect of strain hardening. Further, fractography has been performed on various fracture specimens. Finite Element Modelling of the monotonic tests have also been performed and results are in close agreement with the experimental results. Thus, an overall structure-property correlation has been established by conducting mechanical and microstructural characterization.

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